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# AUTHOR INDEX

*Contribution No.*

ANDERSON, VICTOR C.
(and Philip Rudnick) A thermistor bridge correlator . . . 632

ARTHUR, ROBERT S.
Calculation of refraction factor along a wave ray . . . 631

BASCOM, WILLARD N.
(and Roger R. Revelle) Free-diving: a new exploratory tool . . . 628

BRINTON, EDWARD
*Thysanopoda spinicaudata*, a new bathypelagic giant euphausiid crustacean, with comparative notes on *T. cornuta* and *T. egregia* . . . 652

BUZZATI-TRAVERSO, ADRIANO A.
(and Andreas B. Rechnitzer) Paper partition chromatography in taxonomic studies . . . 606
Paper chromatographic patterns of genetically different tissues: a contribution to the biochemical study of individuality . . . 622

CARHART, RICHARD R.
Reflection of sound in the ocean from temperature changes . . . 637

COE, WESLEY R.
Influences of association, isolation, and nutrition on the sexuality of snails of the genus *Crepidula* . . . 599
Resurgent populations of littoral marine invertebrates and their dependence on ocean currents and tidal currents . . . 604
Bathypelagic nemerteans of the Pacific Ocean . . . 614

ECKHART, CARL H.
The theory of noise in continuous media . . . 608
The propagation of gravity waves from deep to shallow water . . . 621
The scattering of sound from the sea surface . . . 624
Relation between time averages and ensemble averages in the statistical dynamics of continuous media . . . 639
The generation of wind waves on a water surface . . . 648

FOX, DENIS L.
Animal biochromes and structural colours . . . 623a

GERJUOY, EDWARD
Total reflection of waves from a point source . . . 609

HAMILTON, EDWIN L.
Upper Cretaceous, Tertiary, and recent planktonic foraminifera from mid-Pacific flat-topped seamounts . . . 615

HUBBS, CARL L.
(and Robert R. Miller) Hybridization in nature between the fish genera *Catostomus* and *Xyrauchen* . . . 598

Contribution No.

*Eleotris picta* added to the fish fauna of California 600
(and Robert L. Wisner) Food of marlin in 1951 off San Diego, California 601
Geographic and systematic status of the fishes described by Kner and Steindachner in 1863 and 1865 from fresh waters in Panama and Ecuador 610
(and Giles W. Mead and Norman J. Wilimovsky) The widespread, probably antitropical distribution and the relationship of the bathypelagic iniomous fish *Anotopterus pharao* 612
Synonymy of the bathypelagic fish genus *Rhynchohyalus*, referred to the expanded family Argentinidae 625
Identification and relationships of the anchovy described from California as *Anchovia scitula* 626
(and Clark Hubbs) An improved graphical analysis and comparison of series of samples 635
Dolphin protecting dead young 649

HUTTON, WILLIAM E.
(and Claude E. ZoBell) Production of nitrite from ammonia by menthane oxidizing bacteria 605

INMAN, DOUGLAS L.
Areal and seasonal variation in beach and nearshore sediments at La Jolla, California 638

JORGENSEN, C. BARKER
(and Edward D. Goldberg) Particle filtration in some ascidians and lamellibranchs 650

KAMPA, ELIZABETH M.
Effects of vitamin A supplementation and deprivation on visual sensitivity, rhodopsin concentration, and retinal histology of a marine teleost, *gillichthys mirabilis* 613

KNAUSS, J. A.
Shellback expedition 643

McHUGH, J. L.
The influence of light on the number of vertebrae in the Grunion, *Leuresthes tenuis* 636

MAO, HAN-LEE
(and Kozo Yoshida) Physical oceanography in the Marshall Islands area, 20°N-5°S, 155°E-175°E 644

MENARD, HENRY W.
Pleistocene and recent sediment from the floor of the northeastern Pacific Ocean 647

MUNK, WALTER H.
(and Gordon W. Groves) The effect of winds and ocean currents on the annual variation in latitude 602
(and Robert S. Arthur) Wave intensity along a refracted ray 618
Small tsunami waves reaching California from the Japanese earthquake of March 4, 1952 641

NORRIS, ROBERT M.
Buried oyster reefs in some Texas bays 640

*Contribution No.*

OPPENHEIMER, CARL H.
An unusual mortality of California yellowtail (*Seriola dorsalis*) in a marine acquarium 597
Why study marine fish diseases? 629

ORTON, GRACE L.
(and Conrad Limbaugh) Occurrence of an oil globule in eggs of pleuronectid flatfishes 607
The systematics of vertebrate larvae 633
Development and migration of pigment cells in some teleost fishes 634
Dimorphism in larval mouthparts in spadefoot toads of the *Scaphiopus hammondi* group 646

PARKER, FRANCES L.
(and Fred B. Phleger and Jean F. Peirson) Ecology of foraminifera from San Antonio Bay and environs, southwest Texas 603

PHLEGER, FRED B.
(and Frances L. Parker and Jean F. Peirson) North Atlantic foraminifera 619

PINCKARD, J. H.
(and James S. Kittredge, Denis L. Fox, Francis T. Haxo and Laszlo Zechmeister) Pigments from a marine "red water" population of the dinoflagellate *Prorocentrum micans* 623

RIEDEL, WILLIAM R.
Mesozoic and late Tertiary radiolaria of Rotti 654

RUDNICK, PHILIP
The detection of weak signals by correlation methods 611

SCRUTON, PHILIP C.
(and David G. Moore) Distribution of surface turbidity off Mississippi delta 627
Deposition of evaporites 653

SHEPARD, FRANCIS P.
(and Donald B. Sayner) Longshore and coastal currents at Scripps Institution pier 614a
Sedimentation rates in Texas estuaries and lagoons 642
(and Clarence L. Moody) API research project 51—study of near-shore recent sediments and their environments in the northern Gulf of Mexico 651
Submarine canyons 655

SHUMWAY, GEORGE A.
Rafted pebbles from the deep ocean off Baja California 616

SNODGRASS, JAMES H.
(and Dayton E. Carritt and Warren S. Wooster) Automatic servo-operated filter photometer 630

YOSHIDA, KOZO
(and Han-Lee Mao and Paul L. Horrer) Circulation in the upper layer of the equatorial north Pacific 620

ZOBELL, CLAUDE E.
(and Frederick D. Sisler and Carl H. Oppenheimer) Evidence of biochemical heating in Lake Mead mud 617
The occurrence of bacteria in the deep sea and their significance for animal life 645

# LIST OF CONTRIBUTIONS

*from the*

# SCRIPPS INSTITUTION OF OCEANOGRAPHY

NEW SERIES

1953

*Number*

597. OPPENHEIMER, CARL H. An unusual mortality of California yellowtail (*Seriola dorsalis*) in a marine aquarium. Calif. Fish Game, vol. 39, no. 1, pp. 133-135, 1953.

598. HUBBS, CARL L. and ROBERT R. MILLER. Hybridization in nature between the fish genera *Catostomus* and *Xyrauchen*. Pap. Mich. Acad. Sci., vol. 38, pp. 207-233, 1952.

599. COE, WESLEY R. Influences of association, isolation, and nutrition on the sexuality of snails of the genus *Crepidula*. J. exp. Zool., vol. 122, no. 1, pp. 5-19, 1953.

600. HUBBS, CARL L. *Eleotris picta* added to the fish fauna of California. Calif. Fish Game, vol. 39, no. 1, pp. 69-76, 1953.

601. HUBBS, CARL L. and ROBERT L. WISNER. Food of marlin in 1951 off San Diego, California. Calif. Fish Game, vol. 39, no. 1, pp. 127-131, 1953.

602. MUNK, WALTER H. and GORDON W. GROVES. The effect of winds and ocean currents on the annual variation in latitude. J. Met., vol. 9, no. 6, pp. 385-396, 1952.

603. PARKER, FRANCES L., FRED B. PHLEGER and JEAN F. PEIRSON. Ecology of foraminifera from San Antonio Bay and environs, southwest Texas. Spec. Publ. no. 2, Cushman Found., 72 pp., 1953. (Unavailable for exchange.)

604. COE, WESLEY R. Resurgent populations of littoral marine invertebrates and their dependence on ocean currents and tidal currents. Ecology, vol. 34, no. 1, pp. 225-229, 1953.

605. HUTTON, WILLIAM E. and CLAUDE E. ZOBELL. Production of nitrite from ammonia by menthane oxidizing bacteria. J. Bact., vol. 65, no. 2, pp. 216-219, 1953.

606. BUZZATI-TRAVERSO, ADRIANA A. and ANDREAS B. RECHNITZER. Paper partition chromatography in taxonomic studies. Science, vol. 117, no. 3029, pp. 58-59, 1953.

607. ORTON, GRACE L. and CONRAD LIMBAUGH. Occurrence of an oil globule in eggs of pleuronectid flatfishes. Copeia, no. 2, pp. 114-115, 1953.

608. ECKART, CARL H. The theory of noise in continuous media. J. acoust. Soc. Amer., vol. 25, no. 2, pp. 195-199, 1953.

609. GERJUOY, EDWARD. Total reflection of waves from a point source. Commun. pure appl. Math., vol. 6, pp. 73-91, 1953.

610. HUBBS, CARL L. Geographic and systematic status of the fishes described by Kner and Steindachner in 1863 and 1865 from fresh waters in Panama and Ecuador. Copeia, no. 3, pp. 141-148, 1953.

611. RUDNICK, PHIPIP. The detection of weak signals by correlation methods. J. appl. Phys., vol. 24, no. 2, pp. 128-131, 1953.

*Number*

612. Hubbs, Carl L., Giles W. Mead and Norman J. Wilimovsky. The widespread, probably antitropical distribution and the relationship of the bathypelagic iniomous fish *Anotopterus pharao*. BULL. SCRIPPS INSTN. OCEANOGR., vol. 6, no. 5, pp. 173-198, 1953.

613. Kampa, Elizabeth M. Effects of vitamin A supplementation and deprivation on visual sensitivity, rhodopsin concentration, and retinal histology of a marine teleost. *gillichthys mirabilis*. BULL. SCRIPPS INSTN. OCEANOGR., vol. 6, no. 6, pp. 199-224, 1953.

614. Coe, Wesley R. Bathypelagic Nemerteans of the Pacific Ocean. BULL. SCRIPPS INSTN. OCEANOGR., vol. 6, no. 7, pp. 225-286, 1954.

614a. Shepard, Francis P. and Donald B. Sayner. Longshore and coastal currents at Scripps Institution pier. Bull. Beach Eros. Bd., Wash., vol. 7, no. 1, pp. 1-9, 1953. (Unavailable for exchange.)

615. Hamilton, Edwin L. Upper Cretaceous, Tertiary, and recent planktonic foraminifera from mid-Pacific flat-topped seamounts. J. Paleont., vol. 27, no. 2, pp. 204-237, 1953.

616. Shumway, George A. Rafted pebbles from the deep ocean off Baja California. J. sediment. Petrol., vol. 23, no. 1, pp. 24-33, 1953.

617. ZoBell, Claude E., Frederick D. Sisler and Carl H. Oppenheimer. Evidence of biochemical heating in Lake Mead mud. J. sediment. Petrol., vol. 23, no. 1, pp. 13-17, 1953.

618. Munk, Walter H. and Robert S. Arthur. Wave intensity along a refracted ray. Circ. 521, Gravity Waves, U.S. Bur. Stand., pp. 95-108, 1952.

619. Phleger, Fred B., Frances L. Parker and Jean F. Peirson. North Atlantic foraminifera. Reports of the Swedish deep-sea expedition, 1947-1948, vol. 7, Sediment cores from the north Atlantic Ocean, no. 1, 122 pp., 1953.

620. Yoshida, Kozo, Han-Lee Mao and Paul L. Horrer. Circulation in the upper layer of the equatorial north Pacific. J. Mar. Res., vol. 12, no. 1, pp. 99-120, 1953.

621. Eckart, Carl H. The propagation of gravity waves from deep to shallow water. Circ. 521, Gravity Waves, U.S. Bur. Stand., pp. 165-173, 1952.

622. Buzzati-Traverso, Adriano A. Paper chromatographic patterns of genetically different tissues: a contribution to the biochemical study of individuality. Proc. nat. Acad. Sci., Wash., vol. 39, no. 5, pp. 376-391, 1953.

623. Pinckard, J. H., James S. Kittredge, Denis L. Fox, Francis T. Haxo and Laszlo Zechmeister. Pigments from a marine "red water" population of the dinoflagellate *Prorocentrum micans*. Arch. Biochem., vol. 44, no. 1, pp. 189-199, 1953.

623a. Fox, Denis L. Animal biochromes and structural colours. Cambridge University Press, 379 pp., 1953. (Unavailable for exchange.)

624. Eckart, Carl H. The scattering of sound from the sea surface. J. acoust. Soc. Amer., vol. 44, no. 1, pp. 189-199, 1953.

625. Hubbs, Carl L. Synonymy of the bathypelagic fish genus *Rhynchohyalus*, referred to the expanded family Argentinidae. Copeia, no. 2, pp. 96-97, 1953.

626. Hubbs, Carl L. Identification and relationships of the anchovy described from California as *Anchovia scitula*. Copeia, no. 3, pp. 193-194, 1953.

*Number*

627. Scruton, Philip C. and David G. Moore. Distribution of surface turbidity off Mississippi delta. Bull. Amer. Ass. Petrol. Geol., vol. 37, no. 5, pp. 1067-1074, 1953.

628. Bascom, Willard N. and Roger R. Revelle. Free-diving: a new exploratory tool. Amer. Scient., vol. 41, no. 4, pp. 624-627, 1953.

629. Oppenheimer, Carl H. Why study marine fish diseases? J. Cons. int. Explor. Mer., vol. 19, no. 1, pp. 39-42, 1953.

630. Snodgrass, James M., Dayton E. Carritt and Warren S. Wooster. Automatic servo-operated filter photometer. Analyt. Chem., vol. 26, no. 1, pp. 249-250, 1954.

631. Arthur, Robert S. Calculation of refraction factor along a wave ray. Bull. Beach Eros. Bd., Wash., vol. 7, no. 3, pp. 1-12, 1953. (Unavailable for exchange.)

632. Anderson, Victor C. and Philip Rudnick. A thermistor bridge correlator. Rev. sci. Instrum., vol. 24, no. 5, pp. 360-361, 1953.

633. Orton, Grace L. The systematics of vertebrate larvae. Sys. Zool., vol. 2, no. 2, pp. 63-75, 1953.

634. Orton, Grace L. Development and migration of pigment cells in some teleost fishes. J. Morph., vol. 93, no. 1, pp. 69-89, 1953.

635. Hubbs, Carl L. and Clark Hubbs. An improved graphical analysis and comparison of series of samples. Sys. Zool., vol. 2, no. 2, pp. 49-57, 1953.

636. McHugh, J. L. The influence of light on the number of vertebrae in the Grunion, *Leuresthes tenuis*. Copeia, no. 1, pp. 23-25, 1954.

637. Carhart, Richard R. Reflection of sound in the ocean from temperature changes. J. appl. Phys., vol. 24, no. 7, pp. 929-934, 1953.

638. Inman, Douglas L. Areal and seasonal variation in beach and nearshore sediments at La Jolla, California. Tech. Memor. U. S. Army Eros. Bd., no. 39, pp. 1-82, 1953. (Unavailable for exchange.)

639. Eckart, Carl H. Relation between time averages and ensemble averages in the statistical dynamics of continuous media. Phys. Rev., vol. 91, no. 4, pp. 784-790, 1953.

640. Norris, Robert M. Buried oyster reefs in some Texas bays. J. Paleont., vol. 27, no. 4, pp. 569-576, 1953.

641. Munk, Walter H. Small tsunami waves reaching California from the Japanese earthquake of March 4, 1952. Bull. seismol. Soc. Amer., vol. 43, no. 3, pp. 219-222, 1953.

642. Shepard, Francis P. Sedimentation rates in Texas estuaries and lagoons. Bull. Amer. Ass. Petrol. Geol., vol. 37, no. 8, pp. 1919-1934, 1953.

643. Knauss, John A. Shellback expedition. Res. Rev., pp. 1-6, May, 1953.

644. Mao, Han-Lee and Kozo Yoshida. Physical oceanography in the Marshall Islands area, 20°N-5°S, 155°E-175°E. SIO Reference 53-27, 30 pp., 1953. (Unavailable for exchange.)

645. ZoBell, Claude E. The occurence of bacteria in the deep sea and their significance for animal life. IUBS Deep Sea Colloquium, XIV Int. zool. Congr., Copenhagen, 1953. (To be published.)

*Number*

646. Orton, Grace L. Dimorphism in larval mouthparts in spadefoot toads of the *Scaphiopus hammondi* group. Copeia, no. 2, pp. 97-100, 1954.

647. Menard, Henry W. Pleistocene and recent sediment from the floor of the northeastern Pacific Ocean. Bull. geol. Soc. Amer., vol. 64, no. 11, pp. 1279-1294, 1953.

648. Eckart, Carl H. The generation of wind waves on a water surface. J. appl. Phys., vol. 24, no. 12, pp. 1485-1494, 1953.

649. Hubbs, Carl L. Dolphin protecting dead young. J. Mammal., vol. 34, no. 4, p. 498, 1953.

650. Jorgensen, C. Barker and Edward D. Goldberg. Particle filtration in some ascidians and lamellibranchs. Biol. Bull., vol. 105, no. 3, pp. 477-489, 1953.

651. Shepard, Francis P. and Clarence L. Moody. API research project 51—study of near-shore recent sediments and their environments in the northern Gulf of Mexico. SIO reference 53-1, API report no. 7, 30 pp., 1953.

652. Brinton, Edward. *Thysanopoda spinicaudata*, a new bathypelagic giant euphausiid crustacean, with comparative notes on *T. cornuta* and *T. egregia*. J. Wash. Acad. Sci., vol. 43, no. 12, pp. 408-412, 1953.

653. Scruton, Philip C. Deposition of evaporites. Bull. Amer. Ass. Petrol. Geol., vol. 37, no. 11, pp. 2498-2512, 1953.

654. Riedel, William R. Mesozoic and late Tertiary radiolaria of Rotti. J. Paleont., vol. 27, no. 6, pp. 805-813, 1953.

655. Shepard, Francis P. Submarine canyons. C.R. Congr. geol. int., XIX ses., Alger, 1952, sec. 4, Topographie sous-marine et sédimentation actuelle, fasc. 4, pp. 127-149.

# AN UNUSUAL MORTALITY OF CALIFORNIA YELLOWTAIL *(SERIOLA DORSALIS)* IN A MARINE AQUARIUM[1]

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Sometime between the hours of 9 p.m. June 18th and 7 a.m. June 19, 1952, an unusual phenomenon resulted in the death of all the California yellowtail held in captivity at the marine aquarium of the Scripps Institution of Oceanography, La Jolla, California. The 14 fish had been in captivity for several months as an experiment by the California Department of Fish and Game to investigate various types of fish-tagging material. The only other animals in the tank were four sea turtles. The fish were maintained in a 2,500-gallon aquarium tank provided with aeration and constant running sea water collected from the Scripps pier. The water entered the tank from one end at an average flow of approximately 150 gallons per hour. Although it is difficult to calculate the water exchange, it is estimated that a complete change would require from two to three days. The prevailing temperature of the aquarium water at the time of the incident was approximately 17 degrees C. or that of the adjacent ocean water.

On June 18th the yellowtail, apparently in a healthy condition, were fed their semiweekly rations of beef liver which had been thawed from the frozen state. Although the same food was provided to the animals in several of the other aquaria, the yellowtail tank at this time, contrary to usual procedure, was supplied with an excess of beef liver in an attempt to induce the sea turtles to eat. As a result a considerable amount of liver residue was left in the tank, both in fine suspension and in larger pieces on the bottom. At 9 o'clock that night the aquarium curator made his rounds and reported that the fish were apparently in a healthy condition and had a normal appearance.

On the morning following their feeding all the fish were found lying dead at the bottom of the tank, while the four sea turtles were still alive. The water appeared somewhat cloudy and there was a considerable amount of decomposing residue at the bottom of the tank. While the fish were being removed from the tank, much more debris was noticed on the bottom of the tank than could be accounted for by the overfeeding of the fish the previous day. The outward appearance of the fish was normal except that the skin was covered with a heavy mucous coat which was thick and white in appearance with small dark granules. Dissection of the fish revealed a normal appearance of the internal organs except for the fact that the stomachs contained no food. Therefore it was concluded that the fish had regurgitated most or all of the food that had been eaten the previous day. Any remaining food in the stomachs had been digested during the interim. Checking over the history of the fish it was noted that regurgitation had occurred before at infrequent intervals during their captivity.

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[1] Contribution from the Scripps Institution of Oceanography, New Series N. 597. Submitted for publication August, 1952.

Parts of the slime were removed and taken into the laboratory, where they were examined in wet preparation by phase microscopy. The examination showed an oily substance which contained innumerable bacteria of various types. The predominating type appeared to be a rather plump rod approximately one and a half by three microns in length. Many of the bacteria were highly motile, and to all outward appearances the slime was literally filled with bacteria. Phase microscopic examinations were also made of various other parts of the fish and of the water in the aquarium tank. The results of these examinations showed that the aquarium water contained approximately 10 million bacteria per ml which is considered a very heavy concentration. An unusual quantity of mucus had gathered on the surfaces of the gills rendering them somewhat opaque and with only a slightly pinkish tinge instead of the normal bright color. There were many bacteria present on the gill surfaces. Also small rod and coccus types of bacteria were seen among the red and white cells of the blood.

On the same date the other aquaria were examined for bacteria and for their outward appearance. It was noted that all were fairly clear except for one tank which contained the elasmobranchs. A bacteriological examination of the water in these tanks showed the normal numbers of bacteria. A conference with the aquarium maintenance men indicated that the normal flow of water had continued throughout the night. This report was supported by the fact that the water in the aquarium containing the yellowtail had the same temperature as that in the other aquaria. In the other aquaria the fish were all in an apparently normal, healthy condition.

Considering the very rapid and approximately simultaneous death of the yellowtail, it seems improbable that the cause was a specific bacterial or virus disease. There were no outward lesions on the fish and there was no evidence that the fish had struck themselves against the aquarium walls. The animals were apparently normal except for the mucus covering their outer surface and the lack of food in their stomachs.

As no previous mortality of this nature is known to the author, a conclusion as to the cause of the present phenomenon cannot be based on former experiences. However, it is possible to derive a set of tentative conclusions based upon the results obtained by visual and microscopical examinations.

It is well known that beef liver provides an excellent medium for the growth of many bacteria. Therefore, the knowledge that the fish had been overfed the day previous to their death leaving excess liver in the tank would suggest that conditions may have strongly favored the growth of bacteria. This feature, combined with the elevated temperature, would augment the conditions favorable to bacterial growth. Bacteria present in large enough concentration to cause an irritation to the intestinal tract of the fish may have initiated the regurgitation. Acting to increase the supply of readily available organic material in the water of the aquarium, the regurgitated matter would provide a still better medium of growth for bacteria. This may well have accounted for the extremely large number of 10 million bacteria per ml as demonstrated the following morning.

It is assumed that the increased number of bacteria may have accelerated the production of the protective slime over the surface and on the gills of the fish. As this happened the oxygen-absorbing properties of the gills would become reduced and at the same time the numbers of bacteria in the tank, increasing to a point where they could utilize most of the available oxygen in the water, would create partially anaerobic conditions. The observed absence of hydrogen sulfide gas eliminated the possibilities of poisoning by this substance in an anaerobic environment. Combined with the tendency of the mucus to exclude oxygen from the gills, the conditions could certainly cause asphyxiation. One might support these conclusions by the knowledge that bacteria were found in the blood stream of the fish after death. This could conceivably have occurred by the increased numbers of bacteria on the surface of the gills actually penetrating into the small capillaries and invading the blood stream itself while the fish were still living. It seems questionable whether the bacteria were in large enough concentrations in the blood to have been directly responsible for the fatalities.

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# HYBRIDIZATION IN NATURE BETWEEN THE FISH GENERA *CATOSTOMUS* AND *XYRAUCHEN**

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IT HAS recently been demonstrated that the Catostomidae (suckers) are to be included among the several families of freshwater teleost fishes that rather commonly hybridize interspecifically in nature (Hubbs, Hubbs, and Johnson, 1943; Hubbs and Hubbs, 1947; Miller and Miller, 1948, p. 180). In these studies it has been indicated that several species of the North American genus *Catostomus* crossbreed in nature with other species of this genus and with species currently referred to the closely related genus *Pantosteus*. Still more recently we have determined that suckers of the genus *Catostomus* also hybridize, in western North America, with species that are now classified under two other distinct genera, *Chasmistes* and *Xyrauchen*. In this paper we deal with the *Catostomus* × *Xyrauchen* hybrids, referring them to two new interspecific combinations. Both species of *Catostomus* involved have previously been recognized as parents of other natural hybrids.

The species that hybridize with *Xyrauchen* are identified as *Catostomus latipinnis* Baird and Girard in the upper Colorado River system and as *C. insignis* Baird and Girard in the Gila River tributary system. There are no suggestions that they might instead be species of *Pantosteus*, for, unlike the numerous known hybrid individuals involving that genus, the specimens examined exhibit no trace of the highly modified lip characters of *Pantosteus*. Other species of *Catostomus* occurring in the upper Colorado waters are also excluded by the characters of the hybrids. The slender caudal peduncle, flaring caudal fin, long lips with seriated papillae, large fins, and other features indicate that one parental species in the upper river system is *C. latipinnis* rather than *C. commersoni suckleyi* Girard or *C. catostomus griseus* Girard, both of which have recently been transplanted there from the Mississippi watershed. The species of *Catostomus* that hybridizes with *Xyrauchen* in the Gila River system is presumed to be *C. insignis* for two reasons: (1) *C. insignis* was taken with the hybrids and *Xyrauchen*, and (2) the hybrids show specific points of intermediacy between *C. insignis* and *X. texanus*. They differ significantly from the *C. latipinnis* × *X. texanus* hybrids from the upper Colorado system. Thus the caudal peduncle in the *C. insignis* × *X. texanus* hybrids is deeper on the average than in *X. texanus*, as expected, since *C. insignis* has a deeper peduncle than *X. texanus* (Table VII), whereas the *C. latipinnis* × *X. texanus* specimens have a slenderer peduncle than in *X. texanus*, again as expected, since *C. latipinnis* has the slenderest peduncle of any of the forms involved (Table V; Pl. I). In this respect the hybrids of the two combinations are strikingly unlike: in the *C. insignis* × *X. texanus* hybrids the peduncular depth is .093–.099 of the standard length; in the other hybrid combination it is .076–.083. Similar contrast is shown in the number of scales, which is lowest in *C. insignis* and highest in *C. latipinnis*, with the averages intermediate in each hybrid combination (Table II).

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 598, and from the Museum of Zoology, University of Michigan.

That the other parental species in both areas is the huge humpback sucker, *Xyrauchen texanus* (Abbott), admits of no reasonable doubt, for the hybrids exhibit, in diluted form, some of the unique features of that bizarre fish, including its great nuchal hump. *Xyrauchen* is one of the several genera of fishes that are endemic to the Colorado River system (Miller, 1946a).

The possibility that the fish here interpreted as hybrids may instead represent a distinct species, *uncompahgre*, intermediate between *Catostomus* and *Xyrauchen*, or that they may be referable to two such species, seems excluded by circumstantial evidence. Fish of this type have been collected only four times, a single specimen twice and six specimens twice. These collections have been well separated, spatially as well as temporally (1889, 1926, 1947, and 1950). Furthermore, these aberrant specimens agree with known hybrids not only in exhibiting characters intermediate between those of the inferred parental species, but also, as noted above, in being specifically intermediate between the particular local forms of the parental genera. Furthermore, in certain respects, such as the number of scales and the structure of the lips, the hybrids between *C. latipinnis* and *X. texanus* are far more variable than we would expect a species to be.

The criteria adopted in recognizing these new natural hybrids, the methods followed in accumulating and analyzing the data, and the style accepted in presenting the material are essentially the same as those employed by Hubbs, Hubbs, and Johnson (1943, pp. 11–14, 63–73).

We thank Dr. Leonard P. Schultz and his staff for wholehearted coöperation in our studies of pertinent specimens in the United States National Museum (U.S.N.M.). Material recently collected in Utah by Dr. W. F. Sigler has proved of critical value. He, along with Dr. Samuel Eddy, of the University of Minnesota (U.M.), and Dr. William M. Lewis, of Southern Illinois University, have coöperated in providing specimens which had been distributed. The other material used is in the University of Michigan Museum of Zoology (U.M.M.Z.). Robert L. Wisner took some of the X-ray photographs. William L. Cristanelli drafted the graphs and took some of the photographs. Laura C. Hubbs has again contributed her services, especially in the computations.

## *Catostomus latipinnis* × *Xyrauchen texanus*

(Pls. I–III)

U.S.N.M., No. 75992: one wholly immature male 102 mm. in standard length, the holotype and only reported specimen of *Xyrauchen uncompahgre* Jordan and Evermann (in Jordan, 1891, pp. 26–27, pl. 5, fig. 12), collected by David S. Jordan, Barton W. Evermann, and party in Uncompahgre River close to Delta, Colorado; August 14, 1889.

U.S.N.M., No. 143594: one wholly immature female 256 mm. long, seined by Preston and Dorothy Knoch in the Colorado River one-half mile below Fruita Bridge, Mesa County, Colorado; September, 1947.

U.M.M.Z., No. 162334 (five specimens), and U.M., No. 16342 (one specimen): two emaciated males 385 and 391 mm. long, with moderately developed testes, and four females, probably spent, 379–442 mm. long, all collected by W. F. Sigler and party in Green River at Hideout Canyon, nine miles from Vernal Road Junction, Daggett County, Utah (near the Wyoming border); August 5, 1950 (three specimens, 384, 386, and 442 mm. long, had labels reading "Spring Cr.," but are said by Sigler to have been taken in Hideout Canyon or possibly in Sheep Creek, a tributary of the Green River in the same region).

TABLE I

RELATIVE NUMBERS OF CATOSTOMUS LATIPINNIS, HYBRIDS, AND XYRAUCHEN TEXANUS

The data are based on specimens in the United States National Museum and in the Museum of Zoology of the University of Michigan. All specimens were examined by one or both authors. See text for discussion of ratios.

| Specimens in the two collections | *Catostomus latipinnis* |  | Hybrids |  | *Xyrauchen texanus* |  |
|---|---|---|---|---|---|---|
|  | No. | Percentage | No. | Percentage | No. | Percentage |
| In collection containing hybrid |  |  |  |  |  |  |
| U.S.N.M., No. 75992 | 33 | 94.2 | 1 | 2.9 | 1 | 2.9 |
| U.S.N.M., No. 143594 | 0 | 0 | 1 | 50.0 | 1 | 50.0 |
| U.M.M.Z., No. 162334 *et. al.* | 45 | 88.2 | 6 | 11.8 | 0 | 0 |
| From entire upper Colorado River system (above Grand Canyon) | 816 | 97.5 | 8 | 1.0 | 13 | 1.6 |

## RELATIVE NUMBERS OF HYBRIDS AND PARENTAL SPECIES

The relative numbers of hybrids and parental species are no doubt very imperfectly shown by the available data (Table I). The type of *Xyrauchen uncompahgre* (U.S.N.M., No. 75992) was taken (1889) with both putative parental species, but in exactly what numbers cannot be stated, for the specimens were no doubt selected, as was the habit of the time, and the collection has very possibly become in part scattered. The second specimen (U.S.N.M., No. 143594) was seined with one maturing female of *X. texanus* 411 mm. long. No specimens of *Catostomus latipinnis* were preserved in the same series, but that species is widely dispersed throughout the general region and no doubt lives commonly in the river where the hybrid was caught. In the series containing the six large hybrids (U.M.M.Z., No. 162334, and U.M., No. 16342), as it was received at the University of Michigan from previously scattered sources, there are forty-three specimens of *C. latipinnis* and none of *X. texanus*. The collection was made in a deep, swift part of the river, where representative series would be difficult to get, and the preserved sample was perhaps selected. The proportional numbers of *Xyrauchen* (Table I) are probably not closely indicative of the actual population, because of the humpback sucker's habit of returning to deep waters soon after spawning. The humpback was "very abundant in the river channels" of the upper Colorado River system in 1889 (Jordan, 1891, p. 26), but local testimony, from John T. Greenbank and others, indicates that it has become increasingly scarce there in recent years. W. P. Knoch has told us that among about seven hundred suckers caught in 1946 in the Colorado River at the mouth of the Gunnison, only seven were *Xyrauchen*. This great decrease in the numbers of the one species, in the presence of an abundant population of the other, has probably been a major cause of increased frequency of hybridization. Seven of the eight known hybrids between *C. latipinnis* and *X. texanus* were collected since *Xyrauchen* has become scarce in the upper waters. It is probable that the ratio of hybrids to *Xyrauchen* is markedly increasing, though the ratio of hybrids to *C. latipinnis* presumably remains low, almost surely well below 1:100 (except locally, perhaps).

## SEX AND MATURITY

There is no evidence of an unbalanced sex ratio among these hybrids. Of the eight known specimens, three are males, five females.

The fact that the 256-mm. hybrid was wholly immature suggests reduced fecundity, very rapid growth, or delayed maturity, any of which might well be attributed to its origin as a hybrid between a species of *Catostomus* and the .very large *Xyrauchen texanus*. The six large hybrids, 379–442 mm. long, may have spawned. The four females appear to be spent and the emaciation of the two male specimens suggests that they too may have bred. Their testes are moderately enlarged.

## INTERMEDIACY OF HYBRIDS

All eight specimens agree with fish hybrids in general (Hubbs, 1940, pp. 205–9) in being intermediate between the inferred parental species in nearly all differential characters, both of meristic counts (Tables II–IV) and measurements (Table V; Figs. 1–2).

*Meristic counts.*—In number of scales, as represented by the lateral-line count (Table II), the hybrids are extraordinarily variable, and for this reason do not appear to represent a taxonomic unit. The counts are 72, 81–86, and 110—a surprising coverage, of 39, for only eight specimens. Two of the eight counts are beyond the widely separated means of the two parent species, though the average is definitely intermediate. In the dorsal-ray count (Table III) the hybrids are intermediate on the average but approach *Catostomus latipinnis* more closely, and all the counts fall within the range for that species. The lower number of rays in the species of *Catostomus* seems to be imperfectly dominant. The gillraker counts (33, 34, 34, 37, 38, 38, 38, and 38) all fall between the limits of variation for the counts of the parental species (25–32 for *C. latipinnis;* 44–50 for *X. texanus*) (Table IV).

TABLE II

NUMBER OF SCALES ALONG THE LATERAL LINE IN CATOSTOMUS, HYBRIDS, AND XYRAUCHEN

| Locality and form | Lateral-line scales | | |
|---|---|---|---|
| | No. | Range | Mean ± SE |
| Upper Colorado River system | | | |
| *Catostomus latipinnis* | 48 | 90–116 | 103.02 ± 1.03 |
| Hybrids | 8 | 72–110 | 85.25 ± 3.86 |
| *Xyrauchen texanus* | 12 | 69–85 | 77.61 ± 1.32 |
| Gila River system | | | |
| *Catostomus insignis* | 13 | 58–65 | 61.00 ± 0.64 |
| Hybrids | 6 | 62–71 | 66.50 ± 1.41 |
| *Xyrauchen texanus* | 13 | 68–87 | 75.85 ± 1.45 |

*Measurements.*—In differential measurements the eight hybrids are rather consistently intermediate (Table V). Since the hybrids vary greatly in size (102, 256, 379, 384–386, 391, and 442 mm. in

### TABLE III

Number of Dorsal Rays in Catostomus, Hybrids, and Xyrauchen

| Locality and form | Principal dorsal rays | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 11 | 12 | 13 | 14 | 15 | 16 | No. | Range | Mean ± SE |
| Upper Colorado River system | | | | | | | | | | |
| *Catostomus latipinnis* | 1 | 16 | 116 | 56 | 2 | .. | .. | 191 | 10–14 | 12.22 ± .05 |
| Hybrids | .. | .. | 3 | 4 | 1 | .. | .. | 8 | 12–14 | 12.75 ± .25 |
| *Xyrauchen texanus* | .. | .. | ... | .. | 8 | 2 | 2 | 12 | 14–16 | 14.50 ± .23 |
| Gila River system | | | | | | | | | | |
| *Catostomus insignis* | .. | 2 | 8 | 3 | .. | .. | .. | 13 | 11–13 | 12.08 ± .18 |
| Hybrids | .. | .. | 3 | 3 | .. | .. | .. | 6 | 12–13 | 12.50 ± .22 |
| *Xyrauchen texanus* | .. | .. | ... | 2 | 10 | 4 | 1 | 17 | 13–16 | 14.24 ± .18 |

### TABLE IV

Number of Gillrakers in Catostomus, Hybrids, and Xyrauchen

The counts were made on the first arch (both limbs) of the left side and include rudiments. For the upper Colorado River system only specimens more than 100 mm. in standard length were included, as counts indicated that the raker number becomes fixed at about that size. The material from the Gila River system comprises specimens from 52 to 79 mm. long.

| Locality and form | Gillrakers on first arch | | |
|---|---|---|---|
| | No. | Range | Mean ± SE |
| Upper Colorado River system (adults) | | | |
| *Catostomus latipinnis* | 48 | 25–32 | 26.92 ± 0.21 |
| Hybrids | 8 | 33–38 | 36.25 ± 0.77 |
| *Xyrauchen texanus* | 11 | 44–50 | 47.36 ± 0.14 |
| Gila River system (young) | | | |
| *Catostomus insignis* | 25 | 24–30 | 26.16 ± 0.30 |
| Hybrids | 6 | 28–36 | 30.83 ± 1.14 |
| *Xyrauchen texanus* | 13 | 36–43 | 39.92 ± 0.64 |

standard length) and since the proportional measurements of suckers vary greatly with age, the expected average sizes of the parts for the parental species were determined graphically (Figs. 1–2). Since *Xyrauchen* is very poorly represented in collections and seems to

## TABLE V

### Measurements of Catostomus latipinnis, Hybrids, and Xyrauchen texanus

Actual measurements are given for the eight hybrids, along with the average measurements of the parental species at the same sizes, determined graphically (Figs. 1–2). The hybrids and most of the specimens of both parental species were measured by Hubbs; most measurements of the young of *Xyrauchen texanus* were taken by Miller. We followed the methods recommended by Hubbs and Lagler (1947, pp. 13–15, figs. 2–5). Precision dial calipers were used in measuring the smaller parts.

| Measurement | Dimension, in mm. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard length | 101.7 | 256 | 379 | 384 | 385 | 386 | 391 | 442 |
| Body depth | | | | | | | | |
| *C. latipinnis* | 22.0 | 53.0 | 75.0 | 75.7 | 75.8 | 76.0 | 77.0 | 85.6 |
| Hybrid | 24.7 | 61.3 | 92.3 | 82.5 | 87.5 | 88.2 | 78.0 | 92.8 |
| *X. texanus* | 28.5 | 70.7 | 99.7 | 100.7 | 101.0 | 101.3 | 102.5 | 103.6 |
| Depth through pectoral insertion | | | | | | | | |
| *C. latipinnis* | 17.3 | 43.3 | 63.6 | 64.4 | 64.6 | 64.8 | 65.5 | 74.1 |
| Hybrid | 19.9 | 47.65 | 77.3 | 71.7 | 71.4 | 75.7 | 70.0 | 78.3 |
| *X. texanus* | 22.5 | 57.7 | 85.8 | 87.0 | 87.2 | 87.5 | 88.6 | 100.0 |
| Caudal-peduncle depth | | | | | | | | |
| *C. latipinnis* | 6.65 | 17.8 | 26.9 | 27.2 | 27.3 | 27.4 | 27.7 | 31.4 |
| Hybrid | 8.2 | 20.3 | 28.9 | 30.1 | 30.3 | 31.9 | 29.6 | 33.7 |
| *X. texanus* | 9.1 | 22.7 | 33.3 | 33.7 | 33.8 | 33.9 | 34.3 | 38.7 |
| Lips, overall length (A)* | | | | | | | | |
| *C. latipinnis* | 7.1 | 21.7 | 36.3 | 37.0 | 37.2 | 37.3 | 38.0 | 45.0 |
| Hybrid | 6.4 | 18.6 | 23.4 | 32.2 | 31.7 | 33.4 | 34.8 | 33.2 |
| *X. texanus* | 5.2 | 12.4 | 19.7 | 20.0 | 20.1 | 20.2 | 20.6 | 24.4 |
| Gape width (B) | | | | | | | | |
| *C. latipinnis* | 4.9 | 12.2 | 19.1 | 19.4 | 19.5 | 19.5 | 19.8 | 23.3 |
| Hybrid | 6.0 | 13.15 | 19.7 | 23.8 | 19.2 | 23.4 | 22.4 | 24.9 |
| *X. texanus* | 6.1 | 15.2 | 24.2 | 24.6 | 24.7 | 24.8 | 25.3 | 29.2 |
| Separation, lower lips† | | | | | | | | |
| *C. latipinnis* | 0.46 | 1.16 | 1.77 | 1.80 | 1.81 | 1.81 | 1.82 | 2.10 |
| Hybrid | 0.54 | 1.80 | 4.75 | 2.55 | 3.63 | 1.46 | 2.65 | 2.56 |
| *X. texanus* | 1.14 | 3.80 | 6.44 | 6.58 | 6.60 | 6.62 | 6.75 | 8.12 |
| Gillraker, length of longest | | | | | | | | |
| *C. latipinnis* | 1.26 | 3.56 | 5.66 | 5.74 | 5.76 | 5.76 | 5.90 | 6.69 |
| Hybrid | 1.42 | 3.66 | 5.75 | 5.80 | 6.60 | 7.04 | 6.00 | 7.54 |
| *X. texanus* | 1.69 | 4.33 | 6.16 | 6.24 | 6.26 | 6.28 | 6.38 | 7.24 |
| Dorsal fin, length of base | | | | | | | | |
| *C. latipinnis* | 18.8 | 45.6 | 67.0 | 67.8 | 68.0 | 68.2 | 68.9 | 77.8 |
| Hybrid | 22.2 | 54.3 | 78.1 | 73.1 | 81.6 | 77.1 | 74.7 | 87.2 |
| *X. texanus* | 26.1 | 57.1 | 79.8 | 80.7 | 81.0 | 81.1 | 81.9 | 91.0 |
| Interpelvic space | | | | | | | | |
| *C. latipinnis* | 2.6 | 9.3 | 16.5 | 16.9 | 17.0 | 17.0 | 17.3 | ...‡ |
| Hybrid | 3.2 | 12.45 | 12.8 | 14.1 | 20.8 | 20.7 | 13.2 | ... |
| *X. texanus* | 4.1 | 11.8 | 18.1 | 18.4 | 18.5 | 18.5 | 18.75 | ... |
| Ratio, B/A (Fig. 3) | | | | | | | | |
| *C. latipinnis* | 69 | 56 | 53 | 52 | 52 | 52 | 52 | 52 |
| Hybrid | 94 | 71 | 84 | 74 | 61 | 70 | 64 | 75 |
| *X. texanus* | 117 | 123 | 122 | 123 | 123 | 123 | 123 | 120 |

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* Distance from front of upper lip to line joining posterior tips of lobes of lower lip.

† Least distance between papillae at extreme base of lobes of lower lip, but disregarding papillae at isthmus that clearly arise between the lobes.

‡ Values not entered, since at this length the parental species seem not to differ in this character.

vary little in proportions throughout its range, the graphs for that genus are based on specimens from all parts of the Colorado River system. The data for *Catostomus latipinnis* were taken from specimens from the upper Colorado River system in Colorado (mostly) and in northern Utah, at and near the places where the hybrids were

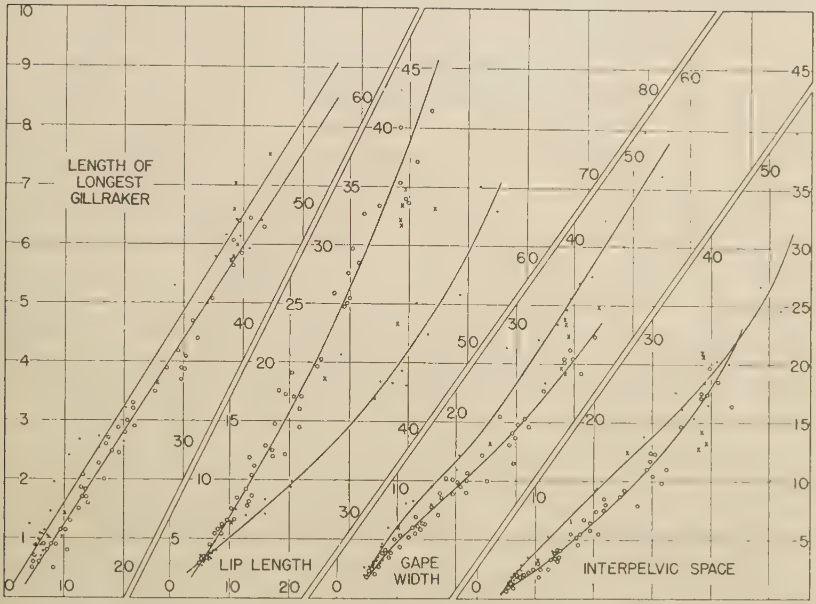


FIG. 1. Relative growth of four parts in *Catostomus latipinnis* (circles) and *Xyrauchen texanus* (solid dots) and corresponding measurements of the eight hybrids (crosses). The specimens of *C. latipinnis* came from the upper Colorado River system in Colorado (mostly) and northern Utah at or near the places where the hybrids were obtained. Those of *X. texanus* are from all parts of the range of the species. The measurements were made by Hubbs. The growth curves were drawn from inspection. Measurements of four additional specimens of *X. texanus* from the Colorado River, Mesa County, Colorado (U.S.N.M., Nos. 132468 and 132469), made after Figures 1 and 2 were prepared, confirm essentially the position of the lines for that species at lengths of 320 to 398 mm., except for the length of the longest gillraker (as noted in the text).

collected. The actual measurements of the hybrids are plotted on the same graphs. The growth lines for the parental species were drawn by inspection. Several types of curves, some not readily subject to conventional analysis through logarithmic transformations, are obviously represented.

Three measurements were taken of the depth, but these are to a large degree independent expressions, though correlated. The greatest body depth (graph not reproduced) varies with condition as well as size, but the plotted measurements clearly separate the parental species, and the hybrids are intermediate. The depth through the insertion of the pectoral fin measures primarily the elevation of the nuchal hump, which is diagnostic of *Xyrauchen* and is partly developed in the hybrids (Pls. I and III). The depth of the caudal peduncle differs noticeably in ecological forms, much more than does the greatest body depth. In some of the largest hybrids the depth values approach those of *Catostomus latipinnis*, probably because they are more or less emaciated. This emaciation affects least the depth through the pectoral insertion, for the hump has a bony base. In this character there is no overlap between the measurements for the parental species, and the values for the hybrids lie very close to the line of separation.

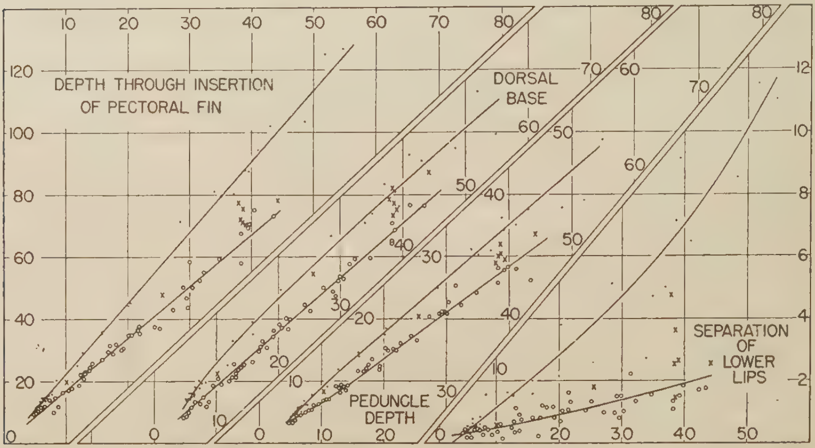


FIG. 2. Relative growth of four parts (not shown in Fig. 1) in *Catostomus latipinnis* (circles), *Xyrauchen texanus* (solid dots), and hybrids (crosses). All measurements were made by Hubbs, except those of the depth of the caudal peduncle and the length of the dorsal-fin base, which were made in part by Miller.

In the overall length of the lips—an extremely variable character, as Rutter (1908, pp. 123–24) pointed out for *Catostomus occidentalis*—the hybrids are intermediate, but six approach *C. latipinnis* much more closely and fall within the upper limit of variation for that parental species. In the basal separation of the lower lips, most of the hybrids come closer to *C. latipinnis*. Of the six large hybrids, one falls outside of the growth curve for *latipinnis*, three resemble that species more than they do *Xyrauchen texanus*, one is almost precisely intermediate, and one comes much nearer to *Xyrauchen*. In the width of the gape the hybrids are more variable: some specimens resemble *C. latipinnis* and others closely approach *X. texanus*, while still others are intermediate. Since the lip is longer and the gape is narrower in *C. latipinnis*, the difference between the parental species is accentuated by expressing the gape width as a percentage of the lip length (Fig. 3). In this proportion, as well as in the lip structures, some of the hybrids approach *X. texanus;* others, *C. latipinnis*. The variation is greater than would be expected within a species.

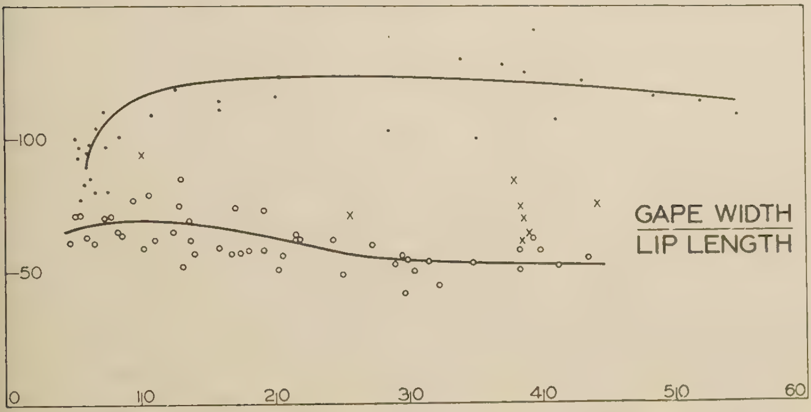


FIG. 3. Change with age in the ratio of gape width to lip length (overall length of both lips) in *Catostomus latipinnis* (circles) and *Xyrauchen texanus* (solid dots), and the ratios of the eight hybrids (crosses). Computed from measurements plotted on Figure 1.

The gillrakers of the smallest hybrid are definitely intermediate in length, as would be expected, since the gillraker lengths of the parental species differ in the young (Fig. 1). When four additional measurements of *Xyrauchen* (taken after Fig. 1 was drawn) are added, the distinction of the adults in respect to raker length largely vanishes, and the hybrids are not very markedly different from either parental species and tend to transgress the averages of both.

In the length of the base of the dorsal fin the parental species overlap to some extent, and all but two of the hybrids are definitely intermediate, much more so than in the number of dorsal rays.

In the interpelvic width the hybrids are extremely variable and even on the average are not intermediate.

Measurements were also taken of head length, head depth, head width, snout length, eye length, longest dorsal ray, the lengths of the anal, pectoral, and pelvic fins, and the width of the pelvic base, but in all these respects the proportions for the two parent species overlap so very widely and the difference between them is so small (less than 5 per cent) as to render the measurements too uncertain for use (and presentation) in determining the relationships of the hybrids to the parental species.

*Unquantified features.*—Even more striking is the intermediacy displayed by the hybrids in various characters, particularly of structure, that have not been quantified.

Like the cyprinid hybrids between *Gila orcutti* and *Siphateles mohavensis* (Hubbs and Miller, 1943, p. 360, pl. 1, figs. 1–3), the *Catostomus latipinnis* × *Xyrauchen texanus* hybrids are intermediate in fundamental scale structure. In *C. latipinnis* the scales are broadly suboval and bear radii on the lateral (dorsal and ventral) as well as on the anterior and posterior fields, whereas in *Xyrauchen* the scales are relatively longer and more rectangular, the lateral fields are largely to wholly devoid of radii, and the anterior border of the scale is distinctively lobate (Ellis, 1914, fig. 59). The hybrids are interjacent in all these respects. They are also intermediate in the poor imbrications of the scales anteriorly, particularly on the belly and the breast, for these scales are rather well imbricated in *C. latipinnis* but are more or less isolated from one another in *X. texanus*.

The gillrakers are intermediate in size and structure as well as in number—a point that was determined after we had already felt some confidence in the hybrid interpretation. They are definitely intermediate in degree of fimbriation, as they also are, conspicuously, in *Catostomus* × *Chasmistes* hybrids. The rakers in *Xyrauchen* approach those of the presumably plankton-eating lacustrine suckers comprising the genus *Chasmistes* not only in number and length but also in fuzziness—apparently adaptations to permit eating minute organisms (in some of the preserved specimens of *Xyrauchen* a sheet of such organisms has been retained between the rakers and the enlarged pharyngeal pad).

Intermediacy is particularly marked in respect to the sharpness, form, and elevation of the nuchal keel, for hardly a trace of this highly diagnostic character of *Xyrauchen* is evident externally in *Catostomus* (Pls. I and III). In the hybrids the keel is distinctly formed, though it is much less strikingly developed than in *Xyrauchen*. The crest of the hump is much more evenly rounded and is located behind rather than before the vertical through the pectoral insertion. Though subject to some variation, the hump of *Xyrauchen* rapidly assumes with age a striking keel and an abrupt far-forward angle (Pl. I, Fig. 3; see also Jordan, 1891, pl. 4, fig. 11; Ellis, 1914, pl. 1, fig. 7; and Simon, 1946, fig. 37). As a result of the development of the keel the occipital region becomes very concave and the nape abruptly convex in *Xyrauchen*. *Catostomus latipinnis* has a weakly and regularly curved anterodorsal profile. The hybrids are intermediate in this respect.

The intermediacy of the hybrids in the development of the nuchal hump is evident in the neural spines of the anterior vertebrae and the anterior interneurals, as well as in the external form. As shown by X-ray photographs, reproduced in part as Plate III, and as indicated by Snyder (1915, pp. 579–80, pls. 76–77), these structures are much more expanded in *Xyrauchen* than in *Catostomus*. According to X-ray pictures of four of the six adult hybrids and exploration by touch, the bones are definitely more expanded in the hybrids than in *C. latipinnis*, but are less enlarged than in *Xyrauchen*. It is noted, however, that the same elements that are greatly expanded in *Xyrauchen* are slightly enlarged in *C. latipinnis*. The degree of expansion of the bones in the hybrids is rather variable.

The hybrids are also intermediate in the flatness of the ventral surfaces between the pectoral fins and between the pelvic fins, regions which are notably flat in *Xyrauchen* and somewhat rounded in *Catostomus latipinnis*, and in the correlated angulation of the bony shoulder girdle in front of the pectoral-fin base.

Particularly striking is the intermediacy in all of the many features that differentiate the lip structures of the parental species (Pl. II). Differences in measurements have already been treated

(p. 216). In *Catostomus latipinnis* both upper and lower lips are very full (Girard, 1859, pl. 24, figs. 1–2). The upper one is strongly papillate over a broad turgid surface; the lower lip is narrowly separated at the extreme base, and the lobes become very markedly elongate with age, suggesting the vernacular name, "flannelmouth sucker." The gape widens less markedly with age than it does in *Xyrauchen*. It remains narrowly instead of broadly U-shaped. As a result of the lengthening of the lips in *C. latipinnis* and the widening of the gape in *X. texanus*, the mouth proportions (Fig. 3) become increasingly and very notably divergent. Conversely, with decreasing size, the differences diminish, until at about 35 mm. standard length the measurements are very similar and the structure is not strikingly different. The distinction between the genera involves chiefly the retention in *Xyrauchen* of juvenile lip structures. The upper lip in that genus remains relatively narrow and less swollen in longitudinal section. It has fewer series of papillae, which are lower and flatter, and is more definitely angulated along the single main row of developed papillae. The lobes of the lower lip remain well separated to the extreme base and do not become greatly elongate, and the inner edges of the gape remain more distinct (Pl. IV, C; also Simon, 1946, fig. 25, 4).

Intermediacy is also seen in the degree of coiling of the intestines. In adults of *Catostomus latipinnis* the region of coiling extends to a point opposite the outer part or end of the pectoral fin; in the larger hybrids it extends to a point between the pectoral tip and the pelvic insertion; and in adults of *Xyrauchen texanus* it extends more or less beyond the pelvic insertion.

There are strong indications of rather variable intermediacy in coloration, also. The hybrids approach *Xyrauchen* in the dark tone of the sides of the body and head and in the relative uniformity of pattern in the dark areas of the body (that is, in the weakness of the characteristic sucker mottling). They appear to be intermediate, also, in the degree of contrast between this dark color and the brightly white lower parts, and in the contrast between the dark borders and the light centers of the scale pockets. These intermediate characters are definitely exhibited by the larger hybrids (Pl. I, Fig. 2), which are fresh and well preserved, and are faintly retained in the old, faded type of *X. uncompahgre*.

### STATUS OF XYRAUCHEN UNCOMPAHGRE

From the data here presented it is clear that the holotype of *Xyrauchen uncompahgre* is intermediate in nearly all characters between *Catostomus latipinnis* and *X. texanus* and is definitely to be regarded as a hybrid. Gilbert and Scofield (1898, p. 492) therefore erred in stating that it agrees with the young of *Xyrauchen* in all characters except the number of dorsal rays, and in concluding that *X. uncompahgre* will probably be found to be the same as *X. cypho* (= *X. texanus*).

### *Catostomus insignis* × *Xyrauchen texanus*

(Pl. IV)

U.M.M.Z., No. 167095: six young specimens 54–78 mm. in standard length, collected by Carl L. and Laura C. Hubbs and Leonard P. Schultz about midway between Roosevelt Dam and Payson, Gila County, Arizona, in the lower part of Tonto Creek, a tributary of Roosevelt Lake, which lies in the course of Salt River of the Gila River system; September 15, 1926.

### RELATIVE NUMBERS OF HYBRIDS AND PARENTAL SPECIES AND SPAWNING RELATIONS

In terms of the effective breeding populations, the relative numbers of *Catostomus insignis* (Table VI) are overweighted and those of *Xyrauchen* underweighted, both for the Tonto Creek collection containing the hybrids and for the combined samples from the whole basin, because most of the collections were made in the smaller streams, where *Catostomus* is more permanently resident. The huge adults of *Xyrauchen* obviously live most of their lives in the larger, deeper waters. Formerly they must have remained chiefly in the main channels of the river and its larger tributaries (Jordan, 1891, p. 26), very probably in deeper holes and other somewhat sheltered situations. Local testimony reported to Jordan (1891, p. 25) and to us indicates that the species once undertook rather extensive upstream spawning migrations. With increased damming and diversion of the streams, the humpback suckers apparently declined greatly in numbers, but the species seems to be readjusting itself to life in the modified waters (Wallis, 1951, p. 89; Douglas, 1952;

personal observations). It is now common in impoundments, particularly in Sahuaro Lake and in other reservoirs in the Salt River system below Roosevelt Lake. Ike Dowell, local commercial fisherman, testified that he caught more than six tons of humpback suckers in Sahuaro Lake during the spawning season in 1949. In Roosevelt Lake, to which Tonto Creek is tributary, and in the Salt River system above that reservoir, the species is now extirpated, according to T. T. Frazier, informed local resident (the lake went completely dry in July, 1930). He said it was common there in 1905, and Hubbs and Schultz collected an adult in the lake at the time they took the hybrids in Tonto Creek (September, 1926). Decreased numbers of *Xyrauchen* may have contributed to the hybridization in that stream. Only a short section of the creek was seined, and the six young hybrids may have stemmed from a single mating.

TABLE VI

RELATIVE NUMBERS OF CATOSTOMUS INSIGNIS, HYBRIDS, AND XYRAUCHEN TEXANUS

The data are limited to catalogued material in the Museum of Zoology in the University of Michigan, since the profuse freshwater-fish collection of that museum is largely composed of unselected mass samples. All specimens have been identified by one or both authors. See text for discussion of ratios.

| Specimens in University of Michigan Museum of Zoology | *Catostomus insignis* | | Hybrids | | *Xyrauchen texanus* | |
|---|---|---|---|---|---|---|
| | No. | Percentage | No. | Percentage | No. | Percentage |
| In collection containing hybrid . . . . | 13 | 40.6 | 6 | 18.7 | 13 | 40.6 |
| From entire Gila River system . . . . | 4,595 | 99.4 | 6 | 0.1 | 20 | 0.4 |

*Xyrauchen* has taken to spawning in the impounded waters of the lower Colorado River basin (Douglas, 1952, and local testimony, particularly for Sahuaro Lake). Sahuaro Lake has no tributaries, and all spawning there must take place in the reservoir. Since other species of the sucker family are absent or very rare in such waters, the incidence of hybridization in the Gila River system and in the lower Colorado River is now presumably very low.

In former years the humpback sucker probably often bred in pool-and-riffle tributaries. Jordan (1891, p. 25) reported local testimony to the effect that this and the other large native fishes of the Colorado River ascended the medium-sized Rio Animas "in the spring, going back to deep water after spawning in the summer." The paucity of young in all collections, however, suggests that most of the fry that hatched in the small streams soon followed the adults into the larger and deeper waters, which have been neglected by collectors.

Whether the hybrids react in intermediate fashion or like one or the other parental species cannot be said. They may act distinctively. Like certain centrarchid hybrids and like the goldfish–carp combination (*Carassius auratus* × *Cyprinus carpio*), as observed by the senior author in the Great Lakes region, they may display heterosis by stemming swift currents with more vigor than either parental species (a reaction that sometimes leads to large concentrations of sterile hybrids).

It is not safe to infer, therefore, that the relative numbers of hybrids and of the parental species indicated in Table VI are closely representative of the actual populations. We may conclude with some confidence, however, that at least under certain conditions *Catostomus insignis* and *Xyrauchen texanus* occasionally hybridize.

## INTERMEDIACY OF HYBRIDS

The *Catostomus insignis* × *Xyrauchen texanus* hybrids are also intermediate between the parental species. They closely resemble the *C. latipinnis* × *X. texanus* crossbreeds, differing chiefly in respects attributable to the differences between the species of *Catostomus* involved in the cross-matings (p. 208).

These hybrids exhibit distinctive intermediacy in scale number (Table II); in the number of dorsal rays, again with a close approach to the *Catostomus* parental species (Table III); and in the number of gillrakers (Table IV). The hybrids of this combination are not exceptionally variable in scale number.

In most measurable characters by which the parental species differ at such small size (between 50 and 80 mm. standard length), the hybrids are intermediate (Table VII). For this combination it was possible to compare the six young hybrids, on the basis of the proportional measurements, with specimens of the parental species of about the same size. For *Xyrauchen texanus* we used the thirteen specimens that were seined with the hybrids. Since only one *Cato-*

*stomus insignis* in this series was small enough, we utilized also six specimens (U.M.M.Z., No. 131118) from the same stream, Tonto Creek, collected above Gisela, and four (U.M.M.Z., No. 131106) from Salt River one mile above the head of Roosevelt Lake, to which Tonto Creek is tributary.

TABLE VII

Proportional Measurements of Catostomus insignis, Hybrids, and Xyrauchen texanus

The measurements are expressed as thousandths of the standard length. The lip and gillraker measurements were made by Hubbs, all others by Miller. We followed the methods recommended by Hubbs and Lagler (1947, pp. 13–15, figs. 2–5). Precision dial calipers were used in measuring the smaller parts, under adequate magnification.

| Measurement | *C. insignis* (11 specimens) | | Hybrids (6 specimens) | | *X. texanus* (13 specimens) | |
|---|---|---|---|---|---|---|
| | Range | Mean | Range | Mean | Range | Mean |
| Standard length, in mm. | 52.6–79.0 | 66.1 | 53.7–77.7 | 71.3 | 57.8–75.7 | 62.1 |
| Caudal-peduncle depth | 81–107 | 100 | 93–99 | 97 | 76–91 | 85 |
| Snout length | 120–131 | 124 | 107–116 | 112 | 99–113 | 107 |
| Eye diameter | 56–70 | 61 | 51–63 | 56 | 50–61 | 56 |
| Lips, overall length* | 57–76 | 68 | 46–63 | 54 | 49–61 | 56 |
| Separation, lower lips† | 1.2–4.1 | 2.7 | 3.3–12.0 | 6.8 | 4.6–10.6 | 8.0 |
| Dorsal fin, depressed length | 294–318 | 304 | 304–344 | 325 | 336–361 | 348 |
| Dorsal fin, length of base | 205–225 | 215 | 213–259 | 235 | 244–274 | 261 |
| Interpectoral space | 98–118 | 109 | 82–108 | 97 | 74–100 | 89 |

* Distance from front of upper lip to line joining posterior tips of lobes of lower lip.

† Least distance between papillae at extreme base of lobes of lower lip, but disregarding papillae at isthmus that clearly arise between the lobes.

In the least depth of the caudal peduncle the approach is closer to *Catostomus insignis*, partly because the range and the mean for that species are lowered by one abnormally slender peduncle measurement. In snout length the approach is closer to *Xyrauchen texanus*, perhaps because the hybrids have the largest average and this proportion decreases with age. In eye length the hybrids agree with *X. texanus*, probably because they are relatively large on the average and the eye decreases rapidly in proportional size with age. For some reason that is not obvious, the lips of the hybrids average even lower in proportional size than those of *X. texanus*. In the two dorsal-fin measurements and in the distance between the pectoral fins the intermediacy is striking.

Five sets of measurements used in checking the intermediacy of the *Catostomus latipinnis* × *Xyrauchen texanus* hybrids were found to be inapplicable to the *C. insignis* × *X. texanus* analysis, because the values for the parental species overlap very widely and the differences between the means is less than 5 per cent. Four sets of measurements that were not applicable to the *C. latipinnis* × *X. texanus* analysis were found useable in the present comparison.

In this combination the intermediacy in scale structure can hardly be said to apply to the general shape of the scale, which is not strikingly different in *Catostomus insignis* and *Xyrauchen texanus*, but it does apply to the greater tendency for radii to develop on the lateral field in *C. insignis* and applies particularly to the number of basal and apical radii, which are most numerous in *C. insignis*, intermediate in the hybrids, and fewest in the young of *X. texanus*. The differences in scale imbrication, and in gillraker structure, are not striking in the young specimens.

Though the nuchal keel is still developing in the young of *Xyrauchen*, the intermediacy of the hybrids is clear-cut in this character. *Catostomus insignis* has no trace of the keel. In the hybrids it is definitely evident, but is less elevated, less firm, less trenchant, and more evenly curved anteriorly than in the young of *X. texanus*. X-ray photographs reveal, under microscopic examination, the intermediacy of the supporting structural elements of the nuchal hump, just as they did for the *C. latipinnis* × *X. texanus* hybrids (Pl. III). As indicated by radiographs of two of the hybrids, these structures are more expanded than in *C. insignis* but are conspicuously less developed than in *X. texanus*.

In this combination as in the other, the hybridity of the aberrant specimens is especially obvious in lip characters (Pl. IV). Except that the lips do not become so excessively elongate in *Catostomus insignis* as they do in *C. latipinnis*, the basic differences in lip structures are similar in the two hybrid combinations and, in both, the hybrids are strikingly intermediate.

Again, the hybrids are intermediate in coloration, and in this combination the intermediacy applies to more characters. In the series of young used for the comparison the large lateral blotches are definitely evident in nearly all of the *Catostomus insignis* specimens, are more or less evident in the hybrids, and are apparent in only the very smallest of the humpback suckers. The spots on the scale pockets, one per scale, that characterize the adults of *C. insignis* are already developing in the young of this species, though in somewhat irregular order and in incomplete series; they are detectable in the hybrids, but are not evident in *Xyrauchen texanus*. The finely penciled dark borders of the scale pockets are strongly developed over most of the body in the young of *X. texanus*, are weaker in the hybrids, though traceable as far forward as the dorsal base, and are very indistinct in the *C. insignis* specimens. In the young of *X. texanus* large melanophores in single series rather consistently line the basal part of the caudal rays; in the young of *C. insignis* such pigment is usually lacking or is developed as minute melanophores irregularly scattered; in the hybrids the development is intermediate. The black peritoneum shows distinctly through the ventral body wall in the smaller specimens of the *X. texanus* series, more weakly in the comparable hybrids, and very weakly or not at all in the young of *C. insignis*.

## Discussion and Conclusions

We regard as incontrovertible the circumstantial evidence that despite its huge size (commonly from twelve to fourteen pounds, occasionally to sixteen pounds), bizarre form, and general preference for large waters, the humpback sucker *Xyrauchen texanus* hybridizes somewhat frequently in nature with two species of *Catostomus*, which, like it, are endemic to the Colorado River fauna. Similar evidence, which we hope to present later, convinces us that the large lacustrine suckers comprising the genus *Chasmistes* also cross with *Catostomus*. We thus extend beyond the limits of *Catostomus* and the closely related group known as *Pantosteus* the list of suckers that interbreed.

Despite their distinctive physiognomy, *Chasmistes* and *Xyrauchen* appear to be phyletically akin to *Catostomus*. It may therefore still be concluded that only closely related genera of Catostomidae hybridize. *Chasmistes* seems to be merely a lacustrine offshoot of

*Catostomus*, evidently adapted by mouth and gillraker structures to feeding chiefly in midwater on plankton, which characteristically abounds in lakes and is poorly developed in streams, rather than on bottom organisms such as predominate in swift water. To some extent, as indicated above, *Xyrauchen* is modified in a similar way. The chief point of its divergence from *Catostomus* lies in peculiarities of form—the flattened breast, the depressed head, and, most notable, the abruptly high and sharp, skeletally supported nuchal hump (Pls. I and III). These peculiarities, which are much less striking in the young than in the adult, are interpretable as adaptations to provide stability and to permit upstream orientation in the almost ceaselessly swift and often torrential flow that characterized the Colorado River and the main stems of its larger tributaries before the recent damming and diversions. Though they may have dropped into quieter pools and recesses where these were available, members of the species must have stemmed such currents during migration and during floods. In form, *Xyrauchen* is remarkably simulated by a cyprinid fish, *Gila cypha*, recently described from the Colorado River in Grand Canyon (Miller, 1946b) and now known to occur elsewhere in the swift sections of the main river. Other fishes of large, swift waters are similarly modified.

There is no apparent phyletic significance in the indication by Snyder (1915, pp. 579–80, pls. 76–77) that the osseous crest of *Xyrauchen* is not much unlike that of *Carpiodes* and *Ictiobus*, which represent the subfamily Ictiobinae (buffalofishes and carpsuckers). As noted above, and as shown on Plate III, the elements of the crest are evident and incipiently modified in *Catostomus latipinnis;* they are similar in *Catostomus insignis*. Nor is much weight to be accorded Snyder's statement that the shape of the fontanelle in *Xyrauchen* and "other peculiar cranial characters," not specified, "indicate no very close relationship between it and *Catostomus*." Nelson's studies of the Weberian apparatus (1948, pp. 237, 241–42) and of the opercular series (1949, p. 563) have linked both *Xyrauchen* and *Chasmistes* with *Catostomus* in the subfamily Catostominae and the tribe Catostomini (which were erected by Hubbs, 1930, p. 9). The reference of *Xyrauchen* and *Chasmistes* as well as *Catostomus* and *Pantosteus* to a single tribe indicates that in the Catostomidae, as in the Poeciliidae and other families, hybridization does not transgress the recognized tribal limits (or the seemingly equivalent relationship in families for which the taxonomic analysis has not yet defined tribes). This close correlation of hybridization with classification raises the question whether the Cyprinidae of eastern and of western North America hybridize more heterogenetically—even between subfamilies according to current classifications—or whether the groups of genera involved may not have been assigned too high a ranking.

It would be flagrantly inconsistent with taxonomic systems, however, to reduce to subspecific status the many species in such families as the Catostomidae and Cyprinidae that do hybridize in nature, even if it could be shown that the hybrids are to some degree fertile. Whether *Xyrauchen* or *Chasmistes* or both (or *Pantosteus*) should be united with *Catostomus* must remain a matter of judgment or authority, but we feel no need to synonymize these genera because they do hybridize with some frequency. Crossability we regard as only one of many systematic criteria, all of which need to be jointly considered in taxonomic ranking.

When a poorly known and troublesome nominal species such as *Xyrauchen uncompahgre* is indicated as having been based on a sporadic interspecific hybrid, it should, of course, be deleted from the system. Such clarifications constitute one of the major contributions from the study of natural hybridization. Since the name *uncompahgre* was not based on a systematic entity, it should be regarded as unavailable.

The newly discovered hybrids again emphasize the generalization that, throughout the teleost series, hybridization between species is much commoner among freshwater than among marine fishes. We think that this interesting but clear-cut contrast may be attributed, in part at least, to the unstable and temporary nature of freshwater habitats and to the increased chance for the meeting of ova and spermatozoa in stream currents. That the hybridization of *Xyrauchen* and of *Chasmistes* with *Catostomus* may be attributable to such chance mixing of the sex products on stream riffles seems very likely, in view of the large discrepancy in size that is typical of these genera and in view of the complex courtship and pairing that characterizes the catostomids (Reighard, 1920).

Enough is known of the habitats and the breeding seasons of *Catostomus* and *Xyrauchen* (and of *Chasmistes*) to make it appear virtually certain that these genera do spawn in close proximity. Some humpback suckers presumably spawn in small streams (where species of *Catostomus* also breed), or at least did so under less modified stream conditions. It is well known that the species of *Catostomus* spawn in the spring. It has been found that *X. texanus* spawns from February well into April in the lower parts of the Colorado River system (local testimony obtained by the junior author and observations by Douglas, 1952, and by us). This species spawns later in the year, though presumably at a comparable season, in the upper Colorado system. Females collected there in May were not yet fully ripe and Jordan (1891, p. 25) reported that *C. latipinnis* and *Xyrauchen* were both said to spawn in the summer in Rio Animas, Colorado.

Another factor that has probably contributed to the hybridization of the two genera, increasingly so in recent years, is the abundance of *Catostomus* and the relative scarcity of *Xyrauchen*. Marked differences in the numbers of the parental species appear to have increased the frequency of hybridization between other species of the Catostomidae (Hubbs and Hubbs, 1947, p. 153), and of other families, such as the Cyprinodontidae (Hubbs, Walker, and Johnson, 1943). Individuals of the rare species are presumably often attracted to the spawning grounds of the common species, where the chance of hybridization is increased, as through the chance meeting of eggs and sperm. When both species are common, minor differences in reactions or behavior presumably keep the spawning groups apart.

## SUMMARY

The genera of the freshwater teleost family Catostomidae that hybridize in nature include *Chasmistes* and *Xyrauchen* as well as *Catostomus* and *Pantosteus*. Two new combinations are described, both between species endemic to the Colorado River system: (1) *Catostomus latipinnis* × *Xyrauchen texanus* (eight specimens, including the holotype of the nominal species *X. uncompahgre*, now deleted from the system), and (2) *Catostomus insignis* × *Xyrauchen texanus* (six specimens, in one collection). These hybrids have occurred sporadically in waters where the parental species have undoubtedly both bred. Greatly reduced numbers of one parental

type (*X. texanus*) has probably increased the incidence of hybridization with the parental species (of *Catostomus*) that have remained abundant.

In being intermediate in most characters between their particular parental species, the newly found catostomid hybrids conform to previously studied interspecific fish hybrids. On the scale grading from 0 for the species of *Catostomus* involved to 100 for *Xyrauchen texanus*, the hybrid indices for the *C. latipinnis* × *X. texanus* hybrids vary from 20 to 70 and average 45 for the three distinctive counts combined; they vary from −9 to 91 and average 42 for the nine major differences in measured proportions; and they vary from −2 to 81 and average 43 for counts and proportions combined. For the six *C. insignis* × *X. texanus* hybrids, the indices vary from 15 to 40 (average, 30) for the three counts; from 24 to 86 (67) for the eight major differences in proportions; and from 24 to 72 (57) for the counts and proportions combined (Table VIII). The aberrant average indices for certain specimens are primarily a consequence of the extreme value of the index representing the interpelvic space. When that index is deleted, the average indices for measurements of each individual of the *C. latipinnis* × *X. texanus* combination vary from 25 to 72 and average 47, and for the counts and measurements together they vary from 24 to 66, with the same average.

The lower number of dorsal rays in the parental species of *Catostomus* appears to be imperfectly dominant over the higher number in *Xyrauchen texanus*.

*Chasmistes* and *Xyrauchen*, though distinctive, are probably close relatives of *Catostomus*, being adaptations respectively to lacustrine and to large, swift river habitats. All these genera are referred to the tribe Catostomini. Hybridization in this as in several other families therefore does not transgress tribal limits. The more heterogenetic crossings indicated for the Cyprinidae suggest that group ranking in that family may have been too high. It would be inconsistent with taxonomic systems to deny specific or even generic rank to forms merely because they hybridize. Crossability is only one of the criteria to be considered.

The new catostomid hybrids may well have resulted from the chance mixing of ova and spermatozoa in stream currents. This

TABLE VIII

Hybrid Indices for Catostomus × Xyrauchen Hybrids

The indices are computed from the data presented or summarized in Tables II–V and VII. Each value indicates the position of the hybrid on a scale of 100 units connecting the means for the *Catostomus* specimens, set at 0, with those for the *Xyrauchen* specimens, set at 100; a value of 50 denotes precise intermediacy.

| Count or measurement | *C. latipinnis* × *X. texanus* (8 specimens) | | | | *C. insignis* × *X. texanus* (6 specimens) | |
|---|---|---|---|---|---|---|
| | 101.7 mm. | 256 mm. | 379–442 mm. (6 specimens) | Mean | Range | Mean |
| Lateral-line-scale count | 87 | 122 | −28–87 | 70 | 7–67 | 37 |
| Dorsal-ray count | −10 | 34 | −10–78 | 23 | −5–43 | 19 |
| Gillraker count | 30 | 49 | 35–54 | 46 | 13–71 | 34 |
| Average for counts | 36 | 68 | 20–70 | 45 | 15–40 | 30 |
| Body depth | 42 | 47 | 4–70 | 41 | ... | ... |
| Depth through pectoral insertion | 50 | 30 | 16–62 | 36 | ... | ... |
| Caudal-peduncle depth | 63 | 51 | 29–69 | 46 | 7–47 | 21 |
| Snout length | .. | ... | ... | .. | 47–100 | 70 |
| Eye diameter | .. | ... | ... | .. | −40–200 | 107 |
| Lips, overall length (A) | 37 | 33 | 18–78 | 38 | 42–183 | 118 |
| Gape width (B) | 93 | 32 | −6–85 | 45 | ... | ... |
| Separation, lower lips | 12 | 24 | −7–64 | 22 | 11–175 | 76 |
| Gillraker, length of longest | 37 | 13 | 12–246 | 84 | ... | ... |
| Dorsal fin, depressed length | .. | ... | ... | .. | 0–91 | 47 |
| Dorsal fin, length of base | 47 | 76 | 41–105 | 68 | −4–96 | 43 |
| Interpectoral space | .. | ... | ... | .. | 5–135 | 57 |
| Interpelvic space | 40 | 126 | −283–253 | −5* | ... | ... |
| Average for measurements | 47 | 48 | −9–91 | 42 | 24–86 | 67 |
| Without interpelvic space | 48 | 38 | 25–72 | 47 | ... | ... |
| Average, counts and measurements | 44 | 53 | −2–81 | 43 | 24–72 | 57 |
| Without interpelvic space | 44 | 46 | 24–66 | 47 | ... | ... |
| Ratio B/A (Fig. 3) | 52 | 22 | 13–45 | 30 | ... | ... |

* Seven specimens.

factor, along with the unstable and ephemeral nature of freshwater habitats, is regarded as a main reason why freshwater fishes hybridize oftener than do marine fishes.

## LITERATURE CITED

DOUGLAS, PHILIP A. 1952. Notes on Spawning Activities of the Humpback Sucker, *Xyrauchen texanus* (Abbott). Calif. Fish and Game, 38 (2): 149–55, figs. 1–4.

ELLIS, MAX M. 1914. Fishes of Colorado. Univ. Colo. Studies, 11: 1–136, 4 figs., pls. 1–12.

GILBERT, CHARLES HENRY, AND NORMAN BISHOP SCOFIELD. 1898. Notes on a Collection of Fishes from the Colorado Basin in Arizona. Proc. U. S. Nat. Mus., 20: 487–99, pls. 36–39.

GIRARD, CHARLES. 1859. Ichthyology of the Boundary. U. S. and Mex. Bound. Surv., 2 (2): 1–85, pls. 1–41.

HUBBS, CARL L. 1930. Materials for a Revision of the Catostomid Fishes of Eastern North America. Misc. Publ. Mus. Zool., Univ. Mich., 20: 1–47.

—— 1940. Speciation of Fishes. Am. Nat., 74: 198–211 (also in Biological Symposia [Lancaster, Pa.: Jaques Cattell Press], II, 7–20).

—— AND LAURA C. HUBBS. 1947. Natural Hybrids between Two Species of Catostomid Fishes. Pap. Mich. Acad. Sci., Arts, and Letters, 31 (1945): 147–67, figs. 1–2.

—— —— AND RAYMOND E. JOHNSON. 1943. Hybridization in Nature between Species of Catostomid Fishes. Contrib. Lab. Vert. Biol., Univ. Mich., 22: 1–76, figs. 1–8, pls. 1–7.

—— AND KARL F. LAGLER. 1947 (2d printing, 1949). Fishes of the Great Lakes Region. Cranbrook Inst. Sci., Bull. 26. xi + 186 pp., figs. 1–251, 26 col. pls., 1 map.

—— AND ROBERT R. MILLER. 1943. Mass Hybridization between Two Genera of Cyprinid Fishes in the Mohave Desert, California. Pap. Mich. Acad. Sci., Arts, and Letters, 28 (1942): 343–78, figs. 1–2, pls. 1–4.

—— BOYD W. WALKER, AND RAYMOND E. JOHNSON. 1943. Hybridization in Nature between Species of American Cyprinodont Fishes. Contrib. Lab. Vert. Biol., Univ. Mich., 23: 1–21, pls. 1–6.

JORDAN, DAVID STARR. 1891. Report of Explorations in Colorado and Utah during the Summer of 1889, with an Account of the Fishes Found in Each of the River Basins Examined. Bull. U. S. Fish Comm., 9 (1889): 1–40, pls. 1–5.

MILLER, ROBERT RUSH. 1946a. The Need for Ichthyological Surveys of the Major Rivers of Western North America. Science, 104: 517–19.

—— 1946b. *Gila cypha*, a Remarkable New Species of Cyprinid Fish from the Colorado River in Grand Canyon, Arizona. Journ. Wash. Acad. Sci., 36: 409–15, fig. 1.

MILLER, ROBERT RUSH, AND RALPH G. MILLER. 1948. The Contribution of the Columbia River System to the Fish Fauna of Nevada: Five Species Unrecorded from the State. Copeia, 1948: 174–87, map 1.

NELSON, EDWARD M. 1948. The Comparative Morphology of the Weberian Apparatus of the Catostomidae and Its Significance in Systematics. Journ. Morph., 83: 225–51, figs. 1–3, pls. 1–3.

—— 1949. The Opercular Series of the Catostomidae. *Ibid.*, 85: 559–67, figs. 1–2.

REIGHARD, JACOB. 1920. The Breeding Behavior of Suckers and Minnows. I. The Suckers. Biol. Bull., 38: 1–32, figs. 1–7.

RUTTER, CLOUDSLEY. 1908. The Fishes of the Sacramento–San Joaquin Basin, with a Study of Their Distribution and Variation. Bull. U. S. Bur. Fish., 27 (1907): 103–52, figs. 1–4, pl. 6.

SIMON, JAMES R. 1946. Wyoming Fishes. Wyo. Game and Fish Dept., Bull. 4: 1–129, figs. 1–92, front.

SNYDER, JOHN OTTERBEIN. 1915. Notes on a Collection of Fishes Made by Edgar A. Mearns from Rivers Tributary to the Gulf of California. Proc. U. S. Nat. Mus., 49: 573–86, 1 fig., pls. 76–77.

WALLIS, ORTHELLO L. 1951. The Status of the Fish Fauna of the Lake Mead National Recreational Area, Arizona–Nevada. Trans. Am. Fish. Soc., 80 (1950): 84–92, fig. 1.

## EXPLANATION OF PLATE I

Left sides of parental species, *Catostomus latipinnis* and *Xyrauchen texanus*, and hybrid

FIG. 1. *Catostomus latipinnis:* adult female, 254 mm. in standard length (U.M.M.Z., No. 162847), from Santa Clara River near Gunlock, Washington County, Utah

FIG. 2. Hybrid: immature female, 256 mm. long (U.S.N.M., No. 143594), from Colorado River, Mesa County, Colorado. Photograph 41–410 from the Smithsonian Institution

FIG. 3. *Xyrauchen texanus:* adult female, 291 mm. long (U.M.M.Z., No. 156798), from Gunnison River at mouth of Kannah Creek, Mesa County, Colorado

Photographs for Figures 1 and 3 by William L. Cristanelli, Institute for Fisheries Research, Ann Arbor

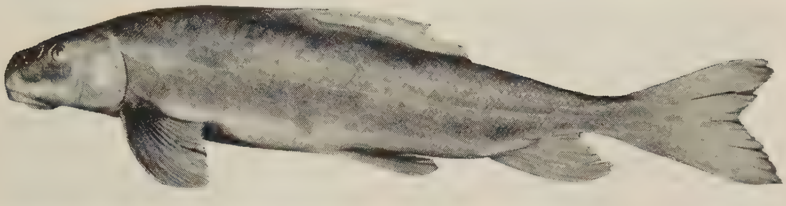


FIG. 1

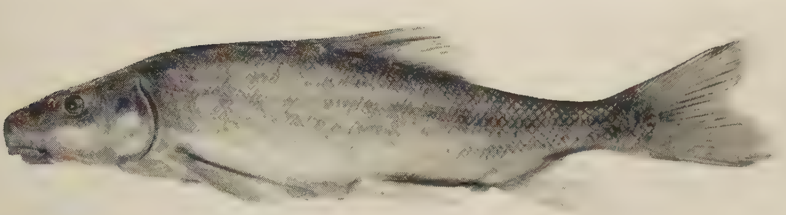


FIG. 2

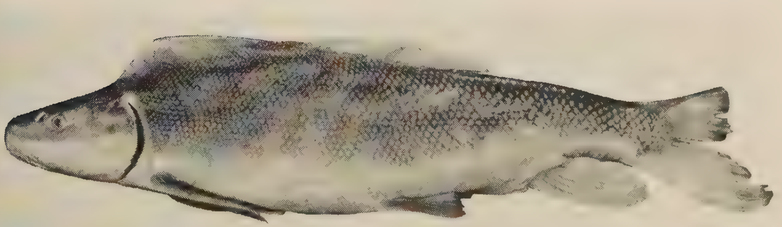


FIG. 3

# EXPLANATION OF PLATE II

Anterior ventral parts of parental species, *Catostomus latipinnis* and *Xyrauchen texanus*, and hybrid

(The specimens are the same as those shown in Pl. I.)

Fig. 1. *Catostomus latipinnis*

Fig. 2. Hybrid. Photograph 41–410A from the Smithsonian Institution

Fig. 3. *Xyrauchen texanus*

Photographs for Figures 1 and 3 by William L. Cristanelli, Institute for Fisheries Research, Ann Arbor

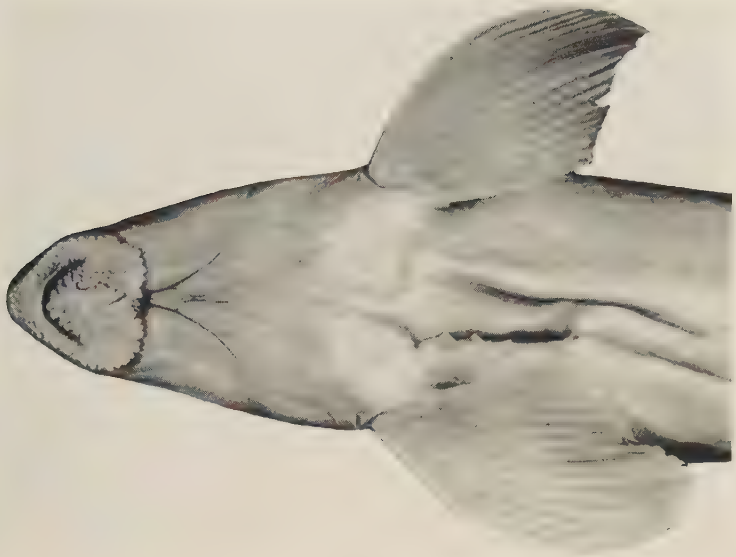


FIG. 1

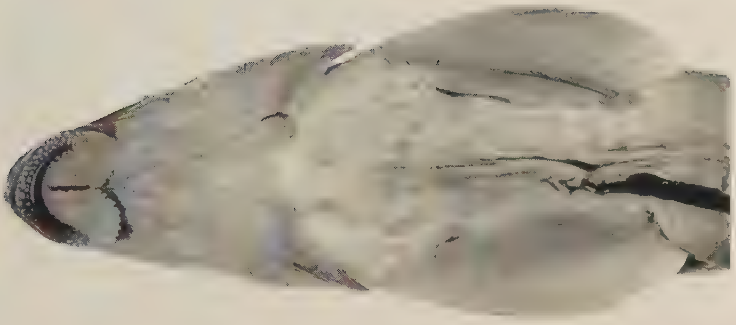


FIG. 2

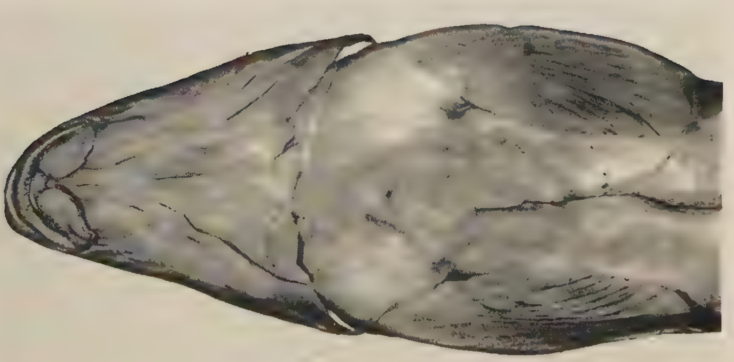


FIG. 3

## EXPLANATION OF PLATE III

Adults of parental species, *Catostomus latipinnis* and *Xyrauchen texanus*, and hybrid; showing development of anterior neurals and interneurals

FIG. 1. *Catostomus latipinnis:* 356 mm. in standard length (U.M.M.Z., No. 160646), from Hideout Canyon (Green River), Utah

FIG. 2. Hybrid: 385 mm. long (U.M.M.Z., No. 162334), from Hideout Canyon (Green River), Utah

FIG. 3. *Xyrauchen texanus,* 291 mm. long; same specimen as shown in Pl. I, Fig. 3

Retouched positive X-ray photographs, from originals
by Robert R. Miller

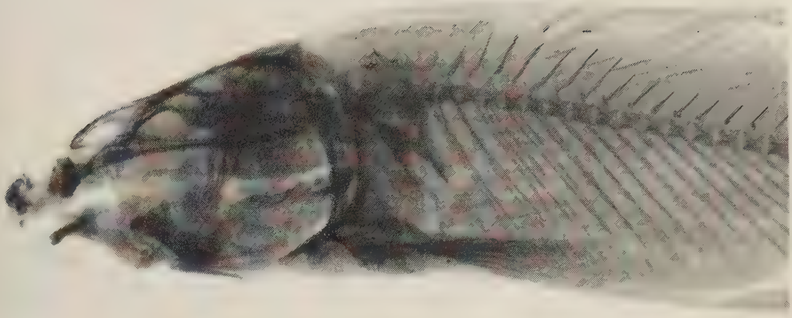


FIG. 1

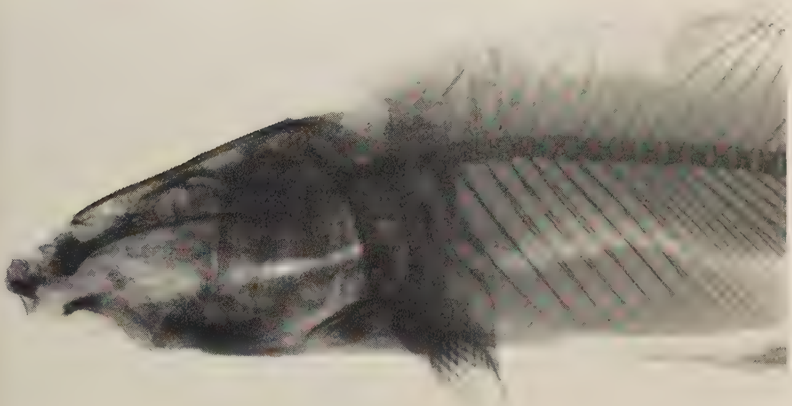


FIG. 2

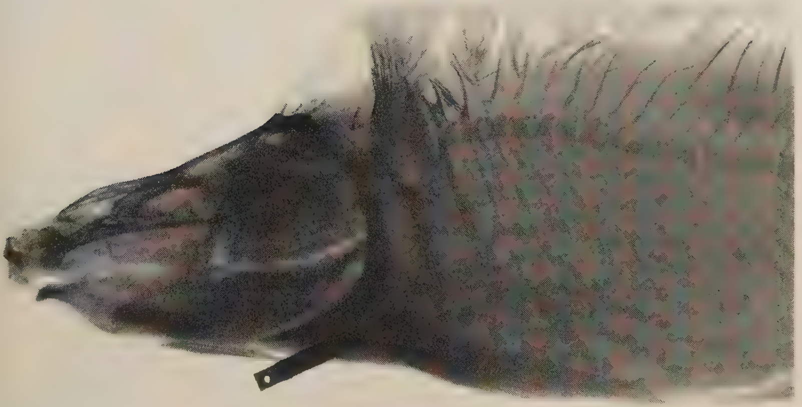
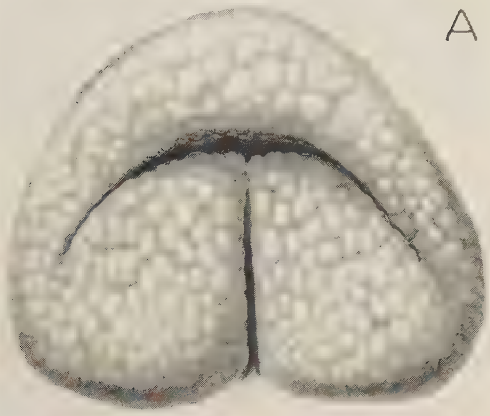
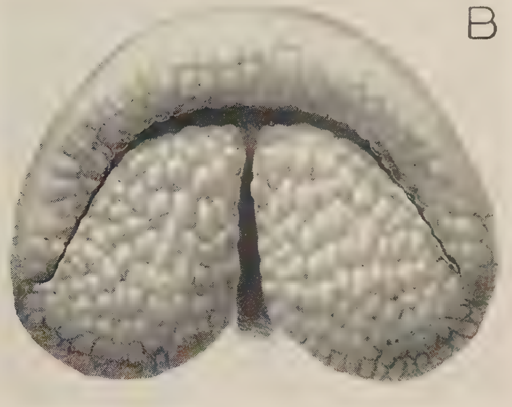


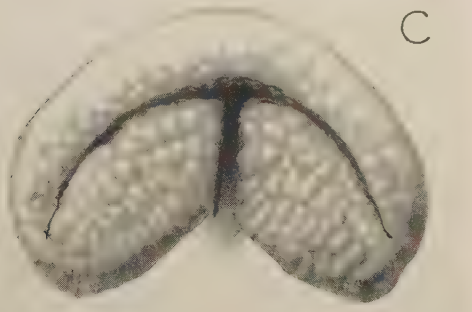
FIG. 3

# EXPLANATION OF PLATE IV

Lips of small specimens of *Catostomus insignis* (A), hybrid (B), and *Xyrauchen texanus* (C). Drawn to the same scale by William L. Brudon, staff artist of the University of Michigan Museum of Zoology. The specimens are of approximately the same standard length (68–70 mm.) and were all collected in Tonto Creek, Arizona.


A


B


C

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# INFLUENCES OF ASSOCIATION, ISOLATION, AND NUTRITION ON THE SEXUALITY OF SNAILS OF THE GENUS CREPIDULA

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TWO FIGURES

Not the least important of the ecological conditions associated with animal and plant populations is the influence of each individual on others of the same species. Some of these influences are the result of stimuli which are transmitted from one individual to the sense organs or other receptors of another individual through the air or water and without physical contact. Presumably these stimuli may effect the liberation of internal secretions which activate certain organs within the body of the recipient and thus influence one or more of the physiological processes, including the behavior of that individual.

Some of the best examples of this influence are found among the Prosobranch gastropods belonging to the family *Calyptraeidae,* in which the behavior and even the sexual development of some of the young snails depends in some degree on association with an older individual of the same species. All the species of this family that have been investigated are irregularly protandric, most individuals passing through a functional male phase when young and later changing to the female phase. The functional male is motile but is usually attached in mating position on the anterior right dorsal surface of the female's shell (fig. 1). The male is provided with a large copulatory organ, or phallus, by means of which the sperm are transferred to the seminal receptacles of the female. The termination of the male phase is followed by a transition stage, during which the phallus is absorbed and the sexual organs peculiar to the male are transformed into those of the female (fig. 2).

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 599.

The writer has cultured many individuals of *Crepidula fornicata* Say and *C. plana* Say of the Atlantic coast and *C. nivea* Adams, *C. norrisiarum* (Williamson), *C. onyx* Sowerby and *C. williamsi* Coe of the Pacific coast, both in the artificial conditions of the laboratory and in the more nearly normal environment of the sea. Some of these were kept in isolation from an early age, while others were associated with older individuals of the same species in the female phase (Coe, '36, '38a, b, '48a, b). With only a few exceptions, those young which were cultured in association with female-phase individuals in the sea, not only developed the functional male phase, but they also experienced a longer and more accentuated male phase than those which were isolated (Coe, '48b). Each species showed some differences from the others in response to these conditions, but the greatest variations were found in *C. plana* and its counterpart on the Pacific coast, *C. nivea*.

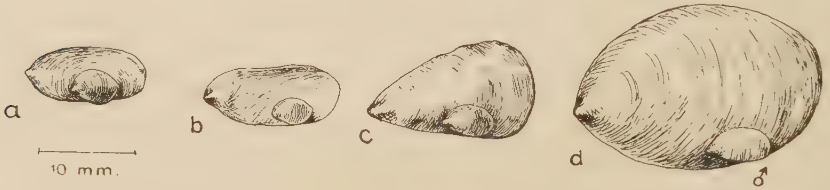

Fig. 1 *Crepidula nivea; a, b,* mature females, dwarf form, with mated males, living in small univalve shells; *c, d,* broad form with males attached in mating position; grown on surface which allowed unlimited space for increase in size. (After Coe, '49.)

### *Crepidula plana*

The sexuality of this species has been more thoroughly investigated than that of any other member of the family, due to the studies of Conklin (1897), Gould ('17a, b, '19, '47, '49, '52), Gould and Hsiao ('48), and Coe ('36, '38a, b, '42, '48a, b). It was formerly supposed that in this species association of the young with a larger individual, of either sex, was essential for the development of the male phase (Gould, '17a, b, '19). It was proved by Coe ('36), however, that also in many isolated young the male phase was developed, while in others the first functional sexual phase was female. This

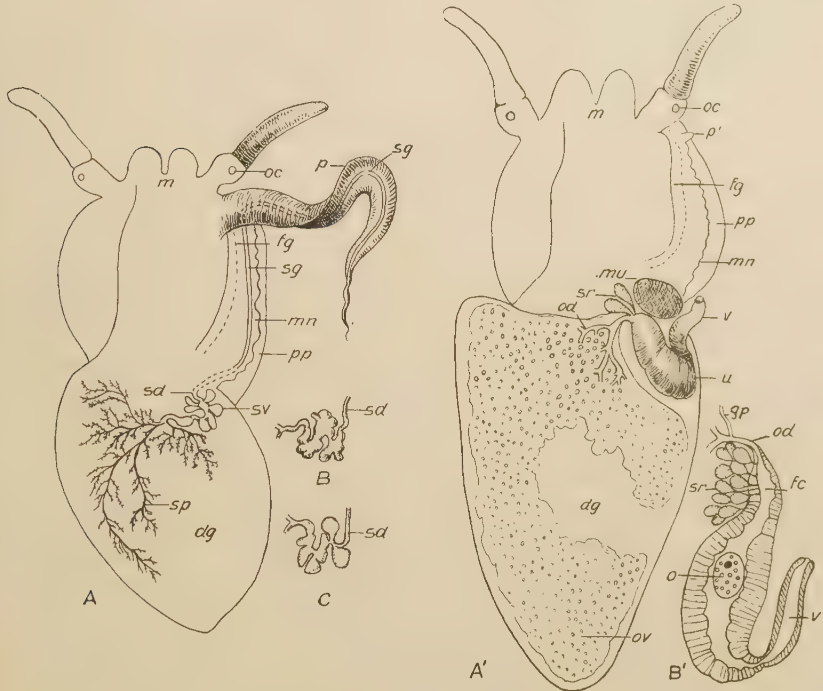

Fig. 2 *Crepidula onyx. A,* Reproductive organs of functional male, showing spermary *(sp),* sperm duct *(sd)* and seminal vesicles *(sv),* with sperm groove *(sg)* near border of mantle *(mm)* and extending along ventral surface of phallus *(p).* Other letters indicate: *dg,* digestive gland; *fg,* food groove; *m,* mouth; *oc,* ocellus; *pp,* propodium. *B, C,* Less sacculated seminal vesicles of other individuals. *A',* Reproductive organs of functional female, showing uterus *(u),* vagina *(v),* 2 of the 12 seminal receptacles *(sr),* oviduct *(od),* gonopericardial duct *(gp),* ovary *(ov),* vestige of the former phallus *(p'),* and right shell muscle *(mu).* Other letters as in figure 1. *B',* Diagrammatic section of uterus and vagina, showing the 12 seminal receptacles *(sr),* each opening by a slender tubule into the fertilization chamber *(fc);* the uterus contains a single ovum *(o).* (After Coe, '42a.)

was later confirmed by Gould and Hsiao ('48), as well as by Gould ('52).

There is usually much variation in the extent of male differentiation in groups of young cultured under identical environmental conditions without the presence of a female-phase individual. These differences appear to result from variations in the multiple hereditary factors on which the sexuality of the individuals depends. It has also been observed that various unfavorable conditions such as lack of food, abnormal temperature or deleterious substances in the water, if not too severe, would allow the young to live and increase in size, but with the suppression of the male phase (Coe, '38b, '48b).

Even the slight differences between the water available in the laboratory and that in the sea from which it came may influence the proportion of isolated young individuals in which the male phase fails to develop. When cultured in the laboratory without additional nutrition or the presence of a female, not more than 10% of the sexually undifferentiated young can be expected to experience a fully developed male phase. With an additional food supply, however, the proportion is greatly increased.

Coe ('48b) has reported simultaneous experiments at the Marine Biological Laboratory at Woods Hole, Massachusetts, in which very young individuals of *C. plana* were isolated in separate vials open at both ends, but covered with netting to prevent the escape of the occupants. One group was cultured in the running water in the laboratory and given a plentiful supply of food, while the other group was placed in an open box suspended in the nearby harbor. Nearly 30% of the 48 isolated young cultured in the laboratory developed an apparently functional male phase if given sufficient nutrition. Many others formed rudiments of the male organs which were soon absorbed and after a period of rapid growth became differentiated as females. Others remained sexually undifferentiated for two weeks or more, increased rapidly in size and showed exclusively female development.

Of the 63 similar young cultured in the harbor, 43, or 68%, assumed a more or less well perfected male phase within a few weeks. In 14 of these, the male characteristics consisted of an incompletely developed phallus and various stages of spermatogenesis. There was no further progress toward the male phase. In the other 29, or 46%, the phallus was well formed and the spermaries and spermatic vesicles filled with active spermatozoa . Only 32% of the 63 young failed to indicate some evidence of the male phase, the gonads of these remaining inactive for several weeks, with female development thereafter They are thought to have had a genetic composition leading directly toward femaleness.

The temperature of the water in the laboratory was usually slightly higher than that in the harbor but the difference in the proportion of the young in which the male phase was developed in the two situations is concluded to have been chiefly due to differences in the available nutrition. The *average* rate of growth, on the contrary, was more rapid in the cultures without the additional food supply than in the harbor or those in the laboratory water with food. The presumable explanation may be found in the proportion of the young which developed the active male phase. Those in which the male phase is most fully developed show little increase in size over a period of several weeks, while those in which that phase is delayed or aborted grow rapidly. Consequently, the greater the proportion of male-phase individuals in a culture, the less the average growth rate. The male phase became functionally developed in about 90% of the young which were cultured with females. The increased proportion of males was accompanied by a decreased average rate of growth.

In experiments on the same species, Gould ('52) likewise found a higher incidence of male development and a lower growth rate in the harbor as compared with similar young in the laboratory. In one of his experiments, in which 10 sexually undifferentiated young were cultured together in the harbor, 6, or 60%, had developed into functional males after 21 days, two had partial male development, and the remaining two were still sexually undifferentiated. In another experiment with a group of 90 young cultured in the laboratory without the association of females, only 4% became functional males, although 43% showed partial male development. Among 61 young associated with females in the laboratory, about 74% completed the development of the male phase. The much higher proportion of young in which the normal male phase fails to develop in the laboratory as compared with similar cultures in the harbor indicates that the water supply in the laboratory is nutritionally deficient or otherwise inadequate for the normal sexual development of the young in this species. Consequently laboratory cultures may lead to erroneous interpretations concerning the normal aspects of sexual differentiation.

### *Crepidula nivea*

This species, often called *C. nummaria*, occurs on the Pacific coast as two ecological forms. The individuals of one of these forms are found on the outside or inside of empty shells of large snails, often occupied also by hermit crabs, as well as on rocks, spiles and other large objects. Large individuals of this form may reach a length of 40 mm or more. The other growth form is found in the apertures of small snail shells and seldom become more than 16 mm in length. In cultures, the young of the slender, dwarf form grow into the broadly oval shape of the large form if allowed a sufficiently large surface for attachment (Coe, '42).

Each large individual in the female phase usually produces more than 5000 eggs at each ovulation. These develop into pelagic larvae which settle down upon solid objects at the end of the free-swimming period. Many of the larvae are carried far from the parent by currents in the water and a large proportion of them doubtless settle beyond the range of influence of any female. Nevertheless, such solitary young are sometimes found in the functional male phase.

In cultures of isolated sexually undifferentiated young, kept in the sea as described for *C. plana,* about 42% developed a more or less well differentiated male phase, as compared with only about 9% of those cultured in the laboratory. This is a smaller proportion of males than was obtained in the similar cultures of *C. plana,* already mentioned. Similar young associated with females and cultured in the sea produced about 90% males.

In order to determine whether in this species the young are attracted to a female-phase individual, as was so fully reported by Gould ('52) for *C. plana,* 30 motile young 4 to 5 mm in length were placed together with one large female which had previously attached itself to the inner wall of a liter jar. After culture in the sea for 24 days, 17 of the young had taken positions on or near the female. All except one of these had developed into males and this one had also made some progress in the direction of the male phase. Of the 13 which were not in the immediate vicinity of the female, 2 had died, 8 were immature females and 3 were males. The experiment indicates that the female not only attracts and detains many of the motile young which may be passing in her vicinity, but also induces male development in some individuals in which that phase would otherwise have been aborted. This is presumably effected by a substance or substances set free in the water, as Gould ('52) has maintained for *C. plana.*

The male phase is generally long continued only when the individual is associated with a female, but occasionally an isolated male remains functional for several weeks. Removing a mated male from his associate usually leads to the prompt termination of the male phase and the initiation of the female phase, but when such an individual is returned to a female, the phallus is restored and the male again becomes functional. This may be repeated if the changes toward the female phase have not proceeded too far.

### *Crepidula williamsi*

Individuals of this species have the same habits and the same two growth forms as mentioned for *C. nivea.* Both species are often found together in the same tidepool, one female, often accompanied by one or more males, in each dead shell of the snail *Tegula,* usually occupied also by a hermit crab. When the shell of *C. williamsi* has become eroded by the movements of the crab, it is almost indistinguishable from that of *C. nivea,* although the animals and the young of the two species differ distinctly and the eggs of the former are about 8 times as large as those of the latter (Coe, '49). There is space for only one female in each *Tegula* shell and while there may be as many as 20 females of *C. nivea* and 10 of *C. williamsi* in one tidepool, it is seldom that a male of one species is associated with a female of the other species, and then not in mating position.

The hereditary factors for protandry are evidently very strong in this species, for the male phase is developed in nearly all the isolated young that are cultured in the sea. The young have not survived well when attempts have been made to culture them in the laboratory.

The eggs are incubated beneath the parent's foot until the young have completed metamorphosis to the adult condition. Soon after hatching, the young snails wander about both on the inside and outside of the *Tegula* shell and migrate to other objects in the vicinity. When cultured in the sea, they become widely scattered along the sides of the container. There is evidently a period of one or two weeks when a female does not attract them but thereafter such an attraction becomes manifest, as the following experiment will indicate.

In order to test the specificity of *C. nivea* and *C. williamsi* relative to the attraction of the female for the young, 12 sexually undifferentiated young of each species were cultured in a liter jar in company with one large female of each species. The females had previously become attached to the inside of the jar with a space of about 11 cm between them. After 22 days in the sea, most of the young had moved about until they had taken positions on or near the female of their own species. Three of the young of *C. nivea* and one of *C. williamsi* remained aloof and after a period of rapid growth those of *C. nivea* eventually developed into females without an intervening male phase. Only one *C. nivea* associated with the appropriate female failed to develop the masculine characteristics. One young of each species died during the experiment, but all the other young of *C. williamsi* developed the male phase. Conchologists have sometimes been unable to distinguish the two species but that difficulty evidently does not present itself to the young snails.

### *Crepidula norrisiarum*

Individuals of this species are most often found on the outside of the shell of the snail *Norrisia norrisi,* usually containing the living animal. The young, which are incubated beneath the parent's foot and have no free-swimming stage, may either attach themselves upon or beside their parents or transfer to another host if afforded the opportunity.

The young snails are about 1 mm long at time of hatching and nearly all of them develop the male phase when isolated and cultured in the sea. Hence, unlike *C. plana* and *C. nivea,* there appears to be little variation in the hereditary factors for sexuality. There is a gradual transition from male to female phases.

### *Crepidula fornicata and C. onyx*

Each of these species, the former on the Atlantic coast and the latter on the Pacific, likewise occurs as two ecological growth forms. The broad form is found on rocks and other large surfaces, as well as on the outside of large snail shells, sometimes with a colony of *C. plana, C. nivea* or *C. williamsi* on the inner surface. Each species appears to have an attraction exclusively for the young of its own kind, since two of the species are not usually mingled. Not infrequently, however, a young *C. plana* will be found on the concave surface of an empty shell of *C. fornicata* or one of *C. nivea* on a similar shell of *C. onyx,* simply as a suitable place for attachment.

When isolated young of *C. onyx* were cultured in the sea, about 90% of them developed the male phase, as compared with 42 to 46% of the isolated young of *C. nivea* and *C. plana* under similar conditions. This would seem to indicate that there is less variability in the heritable sex factors of *C. onyx* than in the other two species.

In some situations 2 to 10 or more individuals are found attached one above the other, with the older individuals in the female phase at the bottom. A male-phase individual, when suitably mated, may retain that phase for a year or more, but when the underlying female is removed from her shell without otherwise disturbing her mate, the latter soon begins the transition to the female phase. A male when tied in mating position on an empty female shell behaves in the same manner. This is further evidence of the influence of the female on the sexuality of her partner (Coe, '38a).

## SUMMARY AND DISCUSSION

Sexually undifferentiated young of 6 species of snails belonging to the genus *Crepidula* have been cultured in widely open glass containers in the laboratory and in the sea, both when separately isolated and when associated with females of the same species.

In each of these species association with females is usual at an early age and such association accentuates and prolongs the initial, male phase but it is not always necessary for the full development of that phase.

The salt water supplies of the laboratories at Woods Hole and at La Jolla are deficient in food materials or otherwise inadequate for development of the sexual organs, although increase in the size of the body may occur. The difficulty may be overcome in part by supplying additional nutrition. This failure of full sexual development is not peculiar to *Crepidula,* but it is the common experience of those who have attempted to culture in the laboratory or aquarium, oysters, clams, mussels, tunicates or other invertebrates which feed, as does *Crepidula,* on microorganisms and particles of detritus suspended in the water. Additional nutrients must be added to the water in order to obtain sexual development and in many cases even for growth. Numerous other observations and experiments have shown that not only the quantity but also the quality of the food influences the sexuality of many unicellular and multicellular organisms, including mollusks (Coe, '48b).

In all the species mentioned, increase in size takes place most rapidly during the transition stages between male and female phases and in those sexually undifferentiated young in which the male phase is to be omitted or aborted. Individuals in the active male phase grow very slowly. Consequently, increasing experimentally the proportion of young which experience the male phase decreases the *average* growth rate of the entire group. Since the proportion of males is greater when the isolated young are cultured in the sea than it is in the less normal conditions of the laboratory, the *average* growth rate is lower in the former situation. It is also lower when the proportion of males is increased by the addition of supplementary nutrients to the water in the laboratory, as well as by association with females. It may be assumed, therefore, that young which have inherited a predominantly female tendency increase in size more rapidly than others under similar conditions.

The experiments indicate that when sexually undifferentiated isolated young of *C. plana* were cultured in the running water of the laboratory not more than one-tenth of them developed the fully differentiated male phase. When additional food was supplied, the proportion was increased to nearly one-third.

When similarly isolated young were cultured in the harbor, a well-perfected male phase was experienced by 46% of the experimental group of 63, while 32% remained sexually undifferentiated and increased rapidly in size for several weeks and developed the female phase thereafter. In the remaining

22% there was partial development of the male organs, but these were soon absorbed and the female phase ensued. Both Coe ('38b) and Gould ('52) concluded that such differences under apparently identical conditions were due to variations in the hereditary sex-differentiating mechanism.

When similar young were cultured in the sea in association with females, about 90% assumed the functional male phase. Hence, it is evident that the presence of the female has induced male development in that proportion of the young in which that phase would otherwise have been aborted or omitted, presumably because of their genetic composition.

Less than one-eighth of the isolated young of *C. nivea* cultured in the laboratory developed the male phase, while that phase was experienced by 42% of those that were cultured in the sea. About 90% of those cultured in the sea in association with females became functional males. The others were evidently so strongly feminine in their inheritance that even the influence of the adult female did not counteract the genetic constitution.

In *C. williamsi, C. norrisiarum, C. fornicata and C. onyx* the presence of the female has much less influence on the development of the male phase, since in most of the isolated young when cultured in the sea the male phase is well developed. The influence of the female, however, is as essential for the accentuation and continuation of that phase as in *C. plana* or *C. nivea*.

Even under the conditions in the laboratory, fully two-thirds of the sexually undifferentiated young of *C. plana* and *C. nivea* which are associated with females develop the functional male phase. The deficiencies in the laboratory water are more than compensated by the influence of the female in eliciting male development.

Suitably mated males may remain functional for several months, but most of the isolated young of *C. plana* and *C. nivea* which develop the male phase, whether in the laboratory or in the sea, retain that phase for only a week or two before beginning the transition to the female phase. Occasionally, however, an isolated male may remain apparently functional for three weeks or more. Even after the male organs have become atrophied in the early transition stage, they may become fully functional again by association with a female. The process may be repeated.

The young of all the species mentioned are motile, and although they usually remain attached to the female throughout the male phase, they are able to move about and reattach themselves if removed. When, because of lack of space or the movements of the hermit crab with which they may be associated, they remain near, but not on, the females' shells, they doubtless move to the copulating position as opportunity permits. This may also occur when several males are present. When the seminal receptacles are well filled, an isolated female of *C. onyx* and presumably of other species may continue to produce fertile eggs for a year or more (Coe, '42a).

During the transition period the two sexeual phases in *C. nivea* and *C. plana* are usually well separated but in the 4 other species mentioned they overlap in most individuals, and the ova begin the deposit of yolk while the seminal vesicles are still filled with active spermatozoa. The uterus and vagina may be well differentiated before the phallus is absorbed and the gonads show a gradual transition from male to female phases.

In conformity with the transformation from male to female phase there is a distinct change in behavior. The individual which was so actively masculine in the earlier phase of sexuality becomes sedentary in the female phase and receives her mate, produces her eggs and deposits them in cellophane-like capsules beneath her foot and then incubates them until the young are hatched.

In all of these species, experiments have shown that many of the motile young which are morphologically undifferentiated sexually appear to be attracted to the vicinity of an individual of the same species which has become, or is becoming, differentiated into the female phase. The female evidently liberates into the water some substance that detains many of the young that may reach her neighborhood. Experiments indicate that the influence is strictly specific, as was demonstrated when the associated young of *C. nivea* and *C. williamsi* were given the choice of a female of each species.

The evidence supports Gould's ('19, '52) conclusion that the same or a similar substance induces the development of the male phase in young individuals with a more feminine type of inheritance and in which that phase would have been omitted or aborted without it. But such a substance is not usually essential for the development of the male phase, since nearly all the isolated young of *C. fornicata*, *C. onyx*, *C. williamsi* and *C. norrisiarum* and nearly half of those of *C. plana* and *C. nivea* become apparently functional male-phase individuals without it.

Physical contact of the young with the female is usual but is not always necessary to induce such masculine development, since the inducing agent seems to be transferred through the water as Gould has demonstrated. Such a substance may also be responsible for the reappearance of functional male organs after a former set has been absorbed in the early transition phase, as well as to accentuate and prolong functional masculinity beyond the time when the transition to the female phase would otherwise have occurred.

It therefore seems reasonable to conclude that the inducing substance stimulates certain sense organs or other receptors on or within the body of the affected individual in such a manner as to elicit the responses that have been mentioned. It is conceivable that internal secretions may be involved, since the behavior as well as the morphological characteristics are changed. When this inducing agent is absent or removed, the genetic factors for a modified form of protandric consecutive sexuality are fully operative, and these factors vary not only with the species but also with the individual.

## LITERATURE CITED

Coe, W. R. 1936 Sexual phases in Crepidula. J. Exp. Zool., *72:* 455–477.

——— 1938a Conditions influencing change of sex in mollusks of the genus Crepidula. J. Exp. Zool., *77:* 401–424.

COE, W. R. 1938b Influence of association on the sexual phases of gastropods having protandric consecutive sexuality. Biol. Bull., *75:* 274–285.

——— 1938c Sexual phases in Crucibulum spinosum. J. Morph., *63:* 345–361.

——— 1942a The reproductive organs of the prosobranch mollusk Crepidula onyx and their transformation during the change from male to female phase. J. Morph., *70:* 501–512.

——— 1942b Influence of natural and experimental conditions in determining shape of shell and rate of growth in gastropods of the genus Crepidula. J. Morph., *71:* 35–51.

——— 1948a Nutrition and sexuality in protandric gastropods of the genus Crepidula. Biol. Bull., *94:* 158–160.

——— 1948b Variations in the expression of sexuality in the normally protandric gastropod Crepidula plana Say. J. Exp. Zool., *108:* 155–170.

——— 1949 Divergent methods of development in morphologically similar species of prosobranch gastropods. J. Morph., *84:* 383–400.

CONKLIN, E. G. 1897 The embryology of Crepidula. J. Morph., *13:* 1–226.

GOULD, H. N. 1917a Studies on sex in the hermaphrodite mollusc Crepidula plana. I. History of the sexual cycle. J. Exp. Zool., *23:* 1–69.

——— 1917b II. Influence of environment on sex. J. Exp. Zool., *23:* 225–250.

——— 1919 III. Transference of the male producing stimulus through sea water. J. Exp. Zool., *29:* 113–120.

——— 1947 Conditions affecting development of the male phase in Crepidula plana. Biol. Bull., *93:* 194.

——— 1949 Effect of temperature on growth and sexual changes in Crepidula plana. Biol. Bull., *97:* 239–240.

——— 1952 Studies on sex in the hermaphrodite mollusk Crepidula plana. IV. Internal and external factors influencing growth and sex development. J. Exp. Zool., *119:* 93–163.

GOULD, H. N., AND S. C. HSIAO 1948 New experiments and observations on sexual instability in Crepidula plana. Biol. Bull., *95:* 255–256.

ISHIKI, H. 1936 Sex changes in the Japanese slipper limpets, Crepidula aculeata and Crepidula walshi. J. Sci. Hiroshima Univ., Ser. B, Div. 1, *4:* 91–99.

ISIKI, H. 1939 Histological studies on the sexual organs during sex changes of Crepidula aculeata and C. walshi. J. Sci. Hiroshima Univ., Ser. B, Div. 1, *6:* 103–113.

# *ELEOTRIS PICTA* ADDED TO THE FISH FAUNA OF CALIFORNIA[1]

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Among the numerous recent additions to the list of California fishes the latest, at the time of writing, is that of the spotted sleeper, *Eleotris picta* Kner and Steindachner. This large gobioid fish has been reported as occurring in coastwise waters, chiefly in the lower parts of rivers, from the regions of Cape San Lucas and Mazatlán in México through Central America to Ecuador (Figure 1).

On April 16, 1952, Clifford Fox of Inglewood, California, caught a specimen (Figure 2) of this species at the canal spillway between Winterhaven and the Colorado River, in Imperial County. Using shrimp for bait, he was fishing about midday on the bottom, at a depth of about four feet, for channel catfish. He reports that the strange fish struck the bait and pulled like a catfish.

The specimen was sent to the author for identification by Arthur F. Halloran, Manager of the Imperial National Wildlife Refuge. It proved to be a non-breeding adult male 11⅛ inches in total length (228 mm. in standard length). It has been deposited in the fish collection of the California Academy of Sciences in San Francisco (Catalog No. 20582).

Mr. Halloran wrote that, so far as could be determined, no fish of this sort had ever been seen in the region. It is highly probable, indeed, that it was a stray from the Gulf of California or from the scarcely collected tidal reaches of the Colorado River. The specimen may have moved directly from the river, a distance of about one-half mile to the spillway, or it may have come from the river through the canal that was overflowing here.

The specimen was confidently identified as *Eleotris picta* because of its close correspondence with the published descriptions and comparisons of that species referred to in the following synonymy, which I have tried to make complete:

*Eleotris picta.*—Kner and Steindachner, in Kner, 1863, p. 223-224 (original diagnosis; questioned as new; "Rio Bayano, Südseite von Panama"). Kner and Steindachner, 1865, pl. 3, fig. 1 (name spelled *pictus* in text). Wagner, 1865, p. 90 (Pacific slope of Panamá). Günther, 1868, p. 389, 441 (Pacific side of Isthmus). Regan, 1906, p. 6-8 (comparisons; diagnosis; Pacific coasts and rivers from California to Ecuador; "Cape St. Lucas"; Mazatlán; Presidio; Colima; Río Bayano, Panamá; Ecuador). Starks, 1906, p. 762, 799 (coloration; Guayaquil, Ecuador; Panamá; Gulf of California; Lower California). Eigenmann, 1910, p. 480 ("Pacific slope, Sonora to Ecuador"). Regan, 1913, p. 472 (Río San Juan, Colombia). Meek, 1914, p. 131 (Pacific coast rivers from California to Ecuador; Río Grande at Orotina, and Jesús María, Costa Rica). Meek and Hildebrand, 1916, p. 356-359 (synonymy; comparisons; description; food; West

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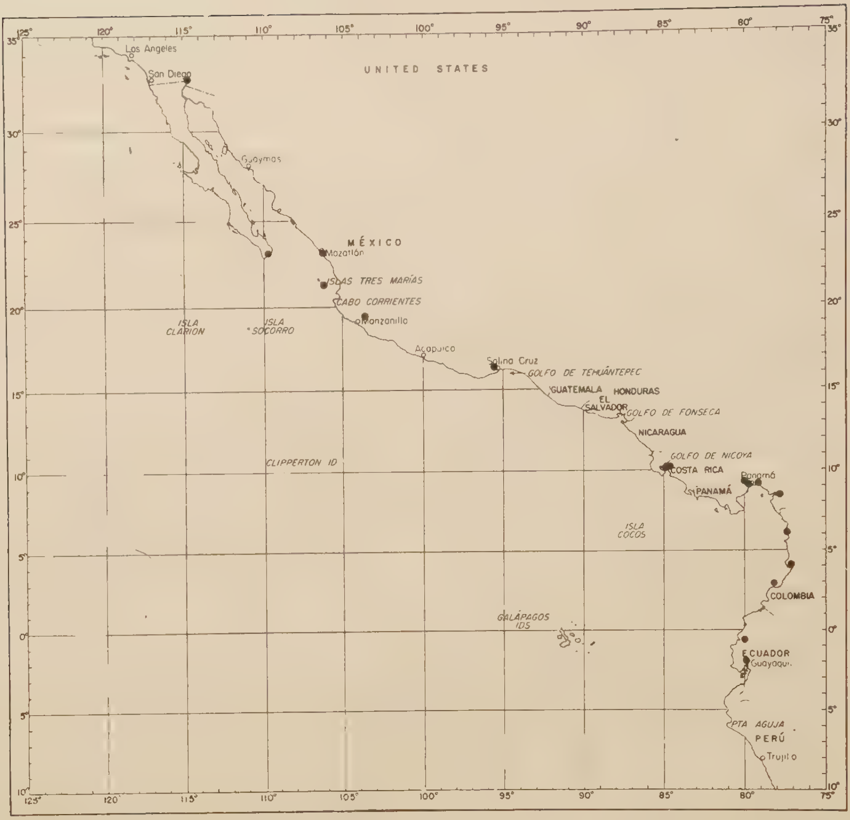
125°
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Los Angeles
San Diego
UNITED STATES
Guaymas
MÉXICO
Mazatlán
ISLAS TRES MARÍAS
CABO CORRIENTES
Manzanillo
ISLA CLARION
ISLA SOCORRO
Acapulco
Salina Cruz
GOLFO DE TEHUÁNTEPEC
GUATEMALA
HONDURAS
EL SALVADOR
GOLFO DE FONSECA
NICARAGUA
CLIPPERTON ID
GOLFO DE NICOYA
COSTA RICA
Panamá
PANAMÁ
ISLA COCOS
COLOMBIA
GALÁPAGOS IDS
ECUADOR
Guayaquil
PTA AGUJA
PERÚ
Trujillo

FIGURE 1. Map of the west coast of the Americas showing by stations the distribution of *Eleotris picta.*

The records have all been published (see synonymy) with the exception of one for Río Tehuántepec and two for Colombia (p. 72) and the one for California. The definite records from Panamá are entered, but the species "has been taken in virtually all the streams sampled in the Pacific slope of Panama" (Hildebrand, 1938, p. 347). Base map drawn by Robert W. Kirk.

From north to south the records are as follows: (1) canal spillway, Imperial County, California; (2) Río San José del Cabo, near Cape San Lucas, Baja California; (3) Río Presidio, near Mazatlán, México; (4) Cleopha Island, Tres Marías group; (5) Colima, México; (6) Río Tehuántepec, México; (7) Jesús María, Costa Rica; (8) Río Grande at Orotina, Costa Rica; (9) Panamá Canal, including Miraflores; (10) Río Bayano, Panamá; (11) Río Chucunaque, Panamá; (12) Río San Juan, Colombia; (13) Puerta Utria, Colombia; (14) Gorgona Island, Colombia; (15) Chone, Ecuador; (16) Guayaquil, Ecuador.

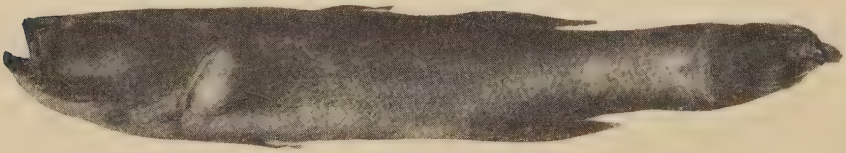

FIGURE 2. First specimen of the spotted sleeper, *Eleotris picta* (family Eleotridae) to be reported from California. Caught in a canal spillway, Imperial County.

Coast and streams, from California to Panamá and Ecuador; lowland streams of the Pacific coast of Panamá eastward to Río Bayano). Eigenmann, 1922, p. 210 (references; Pacific coastal streams from Lower California to Ecuador; Guayaquil market and Chone, Ecuador). Breder, 1927, p. 142, 144, 147, 149, 166 (records and distribution in Río Chucunaque drainage of Río Tuyra system, eastern Panamá; food; comparisons). Hubbs, 1932, p. 68-69 (fresh water, Colima, México). Hildebrand, 1938, p. 344-349 (size; characters of young; compared with *E. pisonis;* some specimens, probably hybrids, combine characters of the two species, presumably as result of intermixture in Panamá Canal; variant with vomerine teeth; anal flap; food; food value; Lower California to Ecuador; in virtually all streams sampled in Pacific slope of Panamá); 1939, p. 20, 29 (hybridization in locks on Pacific side of Panamá Canal, due to contact with *E. pisonis* passing through canal).

*Eleotris pictus.*—Kner and Steindachner, 1865, p. 18-21 (description [usually quoted, wrongly, as the original]; indicated as "n. Sp. ?"; "Neu-Granada [properly "der Isthmusstatt Panama," according to Wagner, 1865, p. 90, footnote 1] und aus dem Rio Bayano"; name spelled *picta* on plate). Günther, 1868, p. 384 (listed). Rutter, 1896, p. 265 (characters; *E. aequidens* as synonym; fresh waters at San José del Cabo, Baja California; Panamá). Jordan and Evermann, 1898, p. 2199-2203 (comparisons; description; synonymy; "streams of the Pacific Coast, from Sonora, south to Panama; abundant in Rio Presidio, at Mazatlan . . . , not rare about Panama"). Gilbert and Starks, 1904, p. 169-170, 216 (characters; comparisons; ponds and ditches at Miraflores, Panamá; Gulf of California). Meek, 1904, p. xxxviii, xxxix, lii, 228-229 (synonymy; comparison; description copied; streams of Pacific coast from Sonora to Panamá; Río Presidio at Presidio, México, and Río San José at San José del Cabo, Baja California). Evermann, 1908, p. 30 (San José del Cabo; references). Eigenmann, 1909, p. 299 (Río Presidio at Mazatlán). Ulrey, 1929, p. 10 (Cape San Lucas). Jordan, Evermann, and Clark, 1930, p. 437 (synonymy; "streams about the Gulf of California, from Sonora south to Panama; Rio Presidio, Mazatlan"). Cuesta Terrón, 1932, p. 80 (Cabo San Lucas). Beltrán, 1934, p. 6 (generic name misspelled *Leotris;* "ríos del Golfo de California, de Sonora hacia el Sur"). de Buen, 1940, p. 64 ("Rio Presidio, cerca Mazatlan. . . . Aguas dulces en San José del Cabo, Baja California. . . ."). Brock, 1943, p. 130 (Sonora to Panamá; fresh water, Cleopha Island, Tres Marías group, at Lat. 21° 17′ N., Long. 106° 15′ W.). Fowler, 1944, p. 516 (Guayaquil and Chone, Ecuador; Panamá; Mazatlán and San José del Cabo, México). de Buen, 1947a, p. 290 ("En Baja California (aguas dulces de San José del Cabo.) Río Presidio"); 1947b, p. 329 ("Cuenca del río Presidio"). Alvarez, 1950, p. 133 (characters in key, compared with *E. pisonis*; name misprinted *pinctus;* "Costa del Pacífico en América, desde Baja California a Centroamérica. Entra en los ríos").

*Culius aequidens.*—Jordan and Gilbert, 1882a, p. 461-462 (original description; near Mazatlán, said to be from fresh water at Presidio); 1882c, p. 372 (Colima, México); 1882d, p. 380 (fresh water near San José, near Cape San Lucas).

*Eleotris aequidens.*—Eigenmann and Fordice, 1885, p. 75-76, 79-80 (comparisons; synonymy; streams about Gulf of California, south to Colima; said to be abundant in streams of Sinaloa and Lower California). Jordan, 1885a, p. 803 (tropical Pacific Coast; fresh waters of western México and Lower California); 1885c, p. 386 (Colima; Cape San Lucas). Jordan and Eigenmann, 1886, p. 483 (streams about Gulf of California, south to Colima). Eigenmann and Eigenmann, 1888, p. 55 (comparisons; Panamá). Jordan, 1889, p. 333 (Río Presidio, near Mazatlán). Eigenmann, 1893, p. 60 (fresh water at Mazatlán and Colima). Jordan, 1895, p. 493 (color, etc.; rather scarce in Río Presidio; a few from brackish waters or muddy places about the estuary).

*Philypnus lateralis* (misidentification, in part—see p. 72).—Jordan and Gilbert, 1882b, p. 368 (in part; Cape San Lucas).

*Eleotris pisonis* (misidentifications).—Eigenmann and Fordice, 1885, p. 75-76, 79-80 (in part; *E. picta* regarded as a synonym; range, in part; Río Bayano, Panamá). Jordan, 1885b, p. 386 (*E. picta* as a synonym; Río Bayano). Jordan and Eigenmann, 1886, p. 483 (*E. picta* as a synonym; range, in part; Río Bayano, Panamá). Eigenmann and Eigenmann, 1891, p. 71 (in part; Río Bayano; *E. pictus* as a synonym). Eigenmann, 1893, p. 60 (Río Bayano [with erroneous citation]).

The published records for the spotted sleeper, duly noted in the synonymy above, and plotted on the accompanying chart (Figure 1), extend northward only to Río Presidio near Mazatlán, Sinaloa, México, near the lower end of the Gulf of California, and to Río San José, near the tip of Baja California. Both localities lie just within the Tropic of Cancer. The specimen from California was taken approximately 750 miles north of the Río San José record and about 860 miles north of the Río Presidio mouth, and, therefore, constitutes a notable extension of known range.

Among unpublished material I can locate no specimens from intervening locations. In the United States National Museum Leonard P. Schultz and Robert Kanazawa locate only four series, with definite data, from north of Panamá: Nos. 2492, Cape San Lucas, John Xantus (two of the specimens reported by Jordan and Gilbert, 1882b, p. 368, as *Philypnus lateralis*); 30943, near San José, L. Belding (reported as *Culius aequidens* by Jordan and Gilbert, 1882d, p. 380); 37142, Río Presidio, Sinaloa, A. Forrer (reported as *E. aequidens* by Jordan, 1889, p. 333); and 102265, Río Tehuántepec, T. MacDougall, 1936. In the Natural History Museum of Stanford University there are, James Böhlke informs me, five series: Nos. 2907, Mazatlán, Sinaloa, México, D. S. Jordan on Hopkins Expedition (reported by Jordan, 1895, p. 493); 6869, Panamá, C. H. Gilbert and party, January 10 to February 24, 1896 (Gilbert and Starks, 1904, p. 169); 8130, San José del Cabo, Baja California, Gustav Eisen (Rutter, 1896, p. 265); 37538, Puerto Utria, Colombia, in stream on mainland opposite tip of peninsula, G. S. Myers on Hancock Expedition, February 25, 1938; 37539, Watering Bay, Gorgona Island, Colombia, in freshwater stream, G. S. Myers, February 24, 1938. In the Museum of Zoology of the University of Michigan, Robert R. Miller finds no cataloged specimens and states that the species is not included in the numerous recent collections made between Mazatlán and the Colorado River by the late Ralph G. Miller. Nor have Boyd W. Walker and his students at the University of California (Los Angeles) secured any in their recent collecting along the shores of the same region. It was not obtained on the recorded collecting expeditions and surveys in the lower Colorado River (Gilbert and Scofield, 1898; Snyder, 1915; Dill, 1944), or on a collecting trip by Hubbs, Miller, and party in March, 1950, along the river from Imperial Dam in California to below the head of tidewater in Baja California.

The published reports from "Lower California" and "Cape San Lucas" obviously refer to the records of *Culius aequidens* from near San José collected by Belding, and of *Eleotris pictus* from fresh waters at San José del Cabo, collected by Eisen (see synonymy). These fish were doubtless taken in Río San José near its mouth, where it flows through the village of San José del Cabo, some miles distant from Cabo San Lucas. This is a perennial stream, with many gobies and other fishes of marine affinities.

Several authors (Jordan and Evermann, 1898, p. 2202; Eigenmann, 1910, p. 480; Meek, 1904 p. 229; Beltrán, 1934, p. 6; and Brock, 1943, p. 130) have indicated that *E. picta* ranges north to Sonora, but I find no basis in previous literature for this extension of the range and presume that "Sonora" was entered for "Sinaloa." Three authorities went farther in stating that the range extends north to California, but I assume that these authors (Regan, 1906, p. 8; Meek, 1914, p. 131; and Meek and Hildebrand, 1916, p. 358) miswrote "California" in place of "Baja California" or "Gulf of California."

This northward extension of the recognized range of *Eleotris picta* adds a genus and a family (Eleotridae) to the California list and adds a species to the known fauna of the United States. The range of the genus and family is thus carried up the West Coast about as far as the genus reaches along the Atlantic Coast. *E. pisonis,* the Atlantic analog of *E. picta,* ranges northward to Texas, Florida, and Georgia and another species, variously identified as *E. abacurus* Jordan and Gilbert or as *E. amblyopsis* (Cope), has been reported from South Carolina, at about the same latitude as Imperial County, California (Jordan, Evermann, and Clark, 1930, p. 437, and Fowler, 1945b, p. 218).

Two other large sleepers (eleotrids), *Gobiomorus maculatus* (Günther) and *Dormitator latifrons* (Richardson), which are commonly associated with *Eleotris picta,* might also stray up the Colorado River into California. Neither, however, has yet been found as far north as the Colorado Delta.

The only gobioid fish that has been reported previously from the lower Colorado River is *Gillichthys detrusus,* which Gilbert and Scofield described from "Horseshoe Bend, near the mouth of the Colorado River, in Mexico," and which we seined in tidal fresh water at the Ponga ferry crossing, due east of a point 8.5 miles south of El Mayor, Baja California (our specimens are all small and heavily parasitized). Incidentally, I have now checked all available specimens of *Gillichthys* from Salton Sea and regard all as referable to the California species, *G. mirabilis* Cooper (see discussion by Miller, 1952, p. 39-40). *G. mirabilis,* the mudsucker, has recently been shown by Willis A. Evans and Philip A. Douglas to be well established in Salton Sea.

The published literature indicates that *Eleotris* is relatively uniform along the margin of the Pacific Coast, not breaking up into species as the genus does along the Atlantic Coast. Two reports (Fowler, 1944b, p. 246, and 1945a, p. 135), however, appear to represent a distinct species, from the Upper Río Jurubidá at Nuquí, in the Province of Chocó, northwestern Colombia, at an elevation of about 3,000 feet. It seems to be characterized by the small number of scales (in only 51 rows along the axis, according to Fowler).

Doubts that now seem resolved have been raised regarding both the pertinence and the gender of the name *Eleotris.* The name has been added to the Official List of generic names, with fixed application to the gobioids of the *E. pisonis* sort. That the name should be regarded as feminine seems clear. It was so treated by the original describers (Bloch and Schneider), and by most subsequent authors, including Cuvier, Bleeker, and Günther. According to current discussions names not occurring in Greek or Latin, with terminations like *-is* that are normal to the third declension, take the gender normal to such words. Such words were either masculine or feminine in classical Latin. The original feminine usage would therefore seem acceptable and is here adopted.

The following color notes were made on the specimen, when fresh, by Arthur F. Halloran and his assistant, Gerald E. Duncan: ''Dark brown on dorsal surface. Yellowish-brown on sides mixed with small yellow spots. Light gray to white, mixed with yellow in spots, on ventral surface forward of anal fin. Dorsal fins dark, with yellow spots. Caudal fin reddish-brown with light streaks on the end. Other fins reddish with dark spots.'' As shown in Figure 2 the lower anterior parts are conspicuously light-spotted.

The spotted sleeper can hardly be regarded as a desirable intrusion into the California fauna and it is hoped that it will not follow the striped mullet (*Mugil cephalus*) and the Pacific ten-pounder (*Elops affinis*) in dispersal from the Colorado River into Salton Sea. It has a low rating as a food or game fish, as Hildebrand (1938, p. 346-347) noted in Panamá. Furthermore, its large, well-toothed mouth, with projecting lower jaw, suggests predatory habits. Several authors (see annotated synonymy) have found that the species eats fish.

## REFERENCES

Alvarez, José

1950. Claves para la determinación de especies en los peces de las aguas continentales mexicanas. Secretaría de Marina, México, p. 1-144, figs. 1-16.

Beltrán, Enrique

1934. Lista de peces mexicanos. Tomado del catálogo de peces en preparación. México, p. 1-13 (processed).

Breder, C. M., Jr.

1927. The fishes of the Rio Chucunaque drainage, eastern Panama. Amer. Mus. Nat. Hist., Bull., vol. 57, art. 3. p. 91-176, figs. 1-9.

Brock, Vernon E.

1943. Distributional notes on the fishes of Lower California and the west coast of Mexico. Copeia, no. 2, p. 130-131.

de Buen, Fernando

1940. Lista de peces de agua dulce de México. En preparación de su catálogo. Estación Limnológica de Pátzcuaro [IV], p. 51-65 (processed).

1947a. Investigaciones sobre ictiología mexicana. I. Catálogo de los peces de la región neárctica en suelo mexicano. Inst. Biol. México, Anal., vol. 18, no. 1, p. 257-292.

1947b. Investigaciones sobre ictiología mexicana. III. Zoogeografía de los peces de agua dulce, con estudio especial de la region neárctica. Inst. Biol. México, Anal., vol. 18, no. 1, p. 304-348.

Cuesta Terrón, Carlos

1932. Lista de los peces de las costas de la Baja California. Inst. Biol. México, Anal., vol. 3, no. 1, p. 75-80.

Dill, William A.

1944. The fishery of the lower Colorado River. Calif. Fish and Game, vol. 30, no. 2, p. 109-211, 37 figs.

Eigenmann, Carl H.

1893. Catalogue of the fresh-water fishes of Central America and southern Mexico. U. S. Nat. Mus., Proc., vol. 16, no. 925, p. 53-60.

1909. The fresh water fishes of Patagonia and an examination of the Archiplata-Archhelenis theory. Princeton Univ. Expeds. to Patagonia, Repts., 1896-1899, vol. 3, pt. 3, p. 295-374, 34 maps, pls. 30-37.

1910. Catalogue and bibliography of the fresh water fishes of the Americas south of the Tropic of Cancer. Princeton Univ. Expeds. to Patagonia, Repts., 1896-1899, vol. 3, pt. 4, p. 375-511.

1922. The fishes of western South America, part I. The fresh-water fishes of northwestern South America, including Colombia, Panama, and the Pacific slopes of Ecuador and Peru, together with an appendix on the fishes of the Rio Meta in Colombia. Carn. Mus., Mem., vol. 9, no. 1, p. 1-346, figs. 1-21, pls. 1-38.

Eigenmann, Carl H., and Rosa Smith Eigenmann

1888. A list of the American species of Gobiidae and Callionymidae, with notes on the specimens contained in the Museum of Comparative Zoology at Cambridge, Massachusetts. Calif. Acad. Sci., Proc., ser. 2, vol. 1, p. 51-78.

1891. A catalogue of the fresh-water fishes of South America. U. S. Nat. Mus., Proc., vol. 14, no. 842, p. 1-81.

Eigenmann, Carl H., and Morton W. Fordice

1885. A review of the American Eleotridinae. Acad. Nat. Sci. Phila., Proc., 1885, p. 66-80.

Evermann, Barton Warren

1908. Descriptions of a new species of trout (*Salmo nelsoni*) and a new cyprinodont (*Fundulus meeki*) with notes on other fishes from Lower California. Biol. Soc. Wash., Proc., vol. 21, p. 19-30.

Fowler, Henry W.

1944a. Results of the Fifth George Vanderbilt Expedition (1941) (Bahamas, Caribbean Sea, Panama, Galápagos Archipelago and Mexican Pacific Islands). Acad. Nat. Sci. Phila., Monog. 6, p. 57-529, figs. 1-268, pls. 1-20.

1944b. Fresh-water fishes from northwestern Colombia. Acad. Nat. Sci. Phila., Proc., vol. 96, p. 227-248, figs. 1-25.

1945a. Colombian Zoological Survey. Part I.—The fresh-water fishes obtained in 1945. Acad. Nat. Sci. Phila., Proc., vol. 97, p. 93-135, figs. 1-47.

1945b. A study of the fishes of the Southern Piedmont and Coastal Plain. Acad. Nat. Sci. Phila., Monog. 7, p. i-vi, 1-408, figs. 1-313.

Gilbert, Charles Henry, and Norman Bishop Scofield

1898. Notes on a collection of fishes from the Colorado basin in Arizona. U. S. Nat. Mus., Proc., vol. 20, p. 487-499, 4 pls.

Gilbert, Charles H., and Edwin C. Starks

1904. The fishes of Panama Bay. Calif. Acad. Sci., Mem., vol. 4, p. 3-304, pls. 1-33.

Günther, Albert

1868. An account of the fishes of the states of Central America, based on collections made by Capt. J. M. Dow, F. Godman, Esq., and O. Salvin, Esq. Zool. Soc. London, Trans., vol. 6, art. 14, p. 377-494, pls. 63-87.

Hildebrand, Samuel F.

1938. A new catalogue of the fresh-water fishes of Panama. Field Mus. Nat. Hist., Zool. Ser., vol. 22, no. 4 (publ. 425), p. 217-359, 13 figs.

1939. The Panama Canal as a passageway for fishes, with lists and remarks on the fishes and invertebrates observed. Zoologica, vol. 24, no. 3, p. 15-45, pls. 1-2.

Hubbs, Carl L.

1932. Studies of the fishes of the order Cyprinodontes. XI. *Zoogoneticus zonistius*, a new species from Colima, Mexico. Copeia, no. 2, p. 68-71.

In Press. Geographic and systematic status of the fishes described by Kner and Steindachner in 1863 and 1865 from fresh waters in Panamá and Ecuador. Copeia 1953, no. 1.

Jordan, David Starr

1885a. A catalogue of the fishes known to inhabit the waters of North America, north of the Tropic of Cancer, with notes on the species discovered in 1883 and 1884. U. S. Comm. Fish and Fish., Ann. Rept. no. 13, p. 787-973 (1-185, sep.).

1885b. A list of the fishes known from the Pacific Coast of tropical America, from the Tropic of Cancer to Panama. U. S. Nat. Mus., Proc., vol. 8, p. 361-394.

1889. List of fishes collected by Alphonse Forrer about Mazatlan, with descriptions of two new species—Heros beani and Poecilia butleri. U. S. Nat. Mus., Proc., vol. 11, 1888, p. 329-334.

1895. The fishes of Sinaloa. Calif. Acad. Sci., Proc., ser. 2, vol. 5, p. 377-514, pls. 27-55.

1896. Notes on fishes little known or new to science. Calif. Acad. Sci., Proc., ser. 2, vol. 6, p. 201-244, 1 pl. + pls. 20-43.

Jordan, David S., and Carl H. Eigenmann

1886. A review of the Gobiidae of North America. U. S. Nat. Mus., Proc., vol. 9, p. 477-518.

Jordan, David Starr, and Barton Warren Evermann

1898. The fishes of North and Middle America . . . . U. S. Nat. Mus., Bull. no. 47, pt. 3, p. i-xxiv, 2183a-3136.

Jordan, David Starr, Barton Warren Evermann, and Howard Walton Clark
1930. Check list of the fishes and fishlike vertebrates of North and Middle America north of the northern boundary of Venezuela and Colombia. U. S. Comm. Fish., Rept. 1928, pt. 2, p. i-iv, 1-670.

Jordan, David S., and Charles H. Gilbert
1882a. Description of five new species of fishes from Mazatlan, Mexico. U. S. Nat. Mus., Proc., vol. 4, 1881, p. 458-463.
1882b. Catalogue of the fishes collected by Mr. John Xantus at Cape San Lucas, which are now in the United States National Museum, with descriptions of eight new species. U. S. Nat. Mus., Proc., vol. 5, p. 353-371.
1882c. List of fishes collected by John Xantus at Colima, Mexico. U. S. Nat. Mus., Proc., vol. 5, p. 371-372.
1882d. List of a collection of fishes made by Mr. L. Belding near Cape San Lucas, Lower California. U. S. Nat. Mus., Proc., vol. 5, p. 378-381.

Kner, Rudolf
1863. Eine Uebersicht der ichthyologischen Ausbeute des Herrn Professors Dr. Mor. Wagner in Central Amerika. Königl. Bayer. Akad. Wissensch. München, 1863, vol. 2, p. 220-230 (attributed in text to Kner and Steindachner).

Kner, Rudolf, and Franz Steindachner
"1864" (1865)[2]. Neue Gattungen und Arten von Fischen aus Central-Amerika; gesammelt von Prof. Moritz Wagner. Königl. Bayer. Akad. Wissensch. München, Abh., vol. 10, pt. 1, p. 1-61, pls. 1-6.

Meek, Seth Eugene
1904. The fresh-water fishes of Mexico north of the Isthmus of Tehuantepec. Field Mus. Nat. Hist., Publ. 93, zool. ser., vol. 5, p. i-lxii, 1-252, figs. 1-72, pls. 1-17, 1 map.
1914. An annotated list of the fishes known to occur in the fresh waters of Costa Rica. Field Mus. Nat. Hist., Publ. 174 (Zool. Ser., vol. 10, no. 10), p. 101-134.

Meek, Seth E., and Samuel F. Hildebrand
1916. The fishes of the fresh waters of Panama. Field Mus. Nat. Hist., Publ. 191 (Zool. Ser., vol. 10, no. 15), p. 217-374, figs. 1-10, pls. 6-32.

Miller, Robert Rush
1952. Bait fishes of the lower Colorado River from Lake Mead, Nevada, to Yuma, Arizona, with a key for their identification. Calif. Fish and Game, vol. 38, no. 1, p. 7-42, 32 figs.

Regan, C. Tate
1906–1908. Pisces. Biologia Centrali-Americana, p. i-xxxiii, 1-203, 26 pls., 7 maps, 1 fig.
1913. The fishes of the San Juan River, Colombia. Ann. and Mag. Nat. Hist., ser. 8, vol. 12, p. 462-473.

Rutter, Cloudsley
1896. Notes on fresh water fishes of the Pacific Slope of North America. Calif. Acad. Sci., Proc., ser. 2, vol. 6, p. 245-267.

Snyder, John Otterbein
1915. Notes on a collection of fishes made by Dr. Edgar A. Mearns from rivers tributary to the Gulf of California. U. S. Nat. Mus., Proc., vol. 49, no. 2125, p. 573-586, 1 fig., pls. 76-77.

Starks, Edwin Chapin
1906. On a collection of fishes made by P. O. Simons in Ecuador and Peru. U. S. Nat. Mus., Proc., vol. 30, no. 1468, p. 761-800, pls. 65-66.

Ulrey, Albert B.
1929. A check-list of the fishes of southern California and Lower California. Pan-Pac. Res. Inst., Jour., vol. 4, no. 4 (printed in Mid-Pac. Mag., vol. 38, no. 4), p. 2-11.

Wagner, Moritz
"1864" (1865)[2] Ueber die hydrographischen Verhältnisse und das Vorkommen der Süsswasserfische in den Staaten Panama und Ecuador. Ein Beitrag zur Zoogeographie Amerika's. Königl. Bayer. Akad. Wissensch. München, Abh., vol. 10, pt. 1, p. 63-113.

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[2] Listed as of 1864 but actually not published until 1865, according to Günther, Zoological Record, 2, 1865 (1866), p. 173; listed in Dean's Bibliography of Fishes as of 1870.

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# FOOD OF MARLIN IN 1951 OFF SAN DIEGO, CALIFORNIA[1]

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The unusual numbers of marlin, *Makaira mitsukurii* (Jordan and Snyder) that were taken by anglers off San Diego in 1950 and 1951[2] provided an opportunity for the determination of its food and other characteristics. Advantage was not taken of this opportunity until late in the 1951 season, when the stomachs of 32 specimens were obtained through the cooperation of Mr. Luther H. Barber, Jr., of the Frosty Freezer in La Jolla and of S. Howard Minor, Jr. and the H and M Sportfishers of San Diego. A. A. Allanson assisted in the procurement of the material.

The marlins were all caught on sport gear near San Diego. All or nearly all came from an arc extending from a few miles west of Point Loma to about five miles southwest of Los Coronados Islands. They were medium-sized adults in the striped phase or of the striped species (we are inclined to the belief that "black marlin" are the older, but not always larger adults of the same species, with thicker bodies and relatively smaller fins and beaks, comparable to the pudgy, dark, unspotted, short-finned adults of the channel catfish, *Ictalurus punctatus* (Rafinesque), that long rated specific recognition—see Hubbs and Allen, 1943, p. 118). The marlin weighed on the average 135 to 140 pounds. One each was caught on August 20 and August 21, 1951; most or all of the others, from October 1 to 26, 1951.

The minimal numbers of individuals of each food item were estimated, usually from counts of the tail ends, which are most persistent. The volumes were roughly measured by water displacement in graduate cylinders. There were rather large sources of error in all these determinations and only close approximations were attempted. Even the rough quantifications, however, are regarded as superior to mere guesswork or verbal statements from visual comparisons. No attempt was made to reconstruct the volumes of largely digested specimens.

Except for small fragments of flesh the food remains, with few exceptions, were identified with little doubt. Clothier's 1950 contribution on the vertebral characters of Southern California fishes was particularly helpful. Incomplete and largely defleshed skeletons were recognized by comparison with the corresponding parts, laid bare, of more complete, readily identifiable remains.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 601. Submitted for publication July, 1952.

[2] S. Howard Minor, Jr., who keeps the local marlin records, reports that at least 585 were caught in 1950 and at least 381 in 1951, in the area from off La Jolla to about Los Coronados Islands.

In both numbers of individuals eaten (907) and volume of food remains (14,656 cc.) the saury, *Cololabis saira* (Brevoort) vastly predominated (Table 1), just as it did in the food of albacore, *Germo alalunga* (Gmelin) of the Pacific Coast, as recently reported by McHugh (1952). The albacore examined by McHugh, however, fed on sauries to the extent of only 30 percent during the period when we find sauries comprising about 75 percent of the food of marlin. The sauries may have been eaten so predominantly merely because they are the most abundant fish of appropriate size in the area just off the close-inshore waters of Southern California.

Had the marlin stayed closer to the shore, northern anchovies, *Engraulis mordax* (Girard), might well have formed the bulk of the food. One marlin, caught rather close to shore, 9 miles southwest of Point Loma on August 20, contained more than half (1,395 cc.) of the total volume of anchovy remains removed from all 32 stomachs (in addition, this fish contained only one saury head, measuring 2 cc.). The northern

TABLE 1

Food Contents of 32 Marlin Caught Near San Diego in 1951

| Species of food[1] | Estimated number | | | Volume of remains, cc. | | |
|---|---|---|---|---|---|---|
| | Total | Ave. per marlin | Percent of fish food | Total | Ave. per marlin | Percent of fish food |
| Saury | 907 | 28.3 | 75.5 | 14,656 | 458 | 72.4 |
| Northern anchovy | 249 | 7.8 | 20.7 | 2,362 | 74 | 11.7 |
| Pacific sardine | 21 | 0.7 | 1.7 | 1,742 | 54 | 8.6 |
| Jack mackerel | 20 | 0.6 | 1.7 | 591 | 18 | 2.9 |
| Pacific mackerel | 2 | 0.1 | 0.2 | 153 | 5 | 0.8 |
| Halfmoon | 1 | trace | 0.1 | 6 | trace | trace |
| Bonito (?) | 1 | trace | 0.1 | trace | trace | trace |
| Unidentified fish fragments | ? | ? | ? | 745 | 23 | 3.7 |
| Total fish | 1,201+ | 37.5 | 100 | 20,255+ | 633 | 100 |
| Squid | 3–6 | 0.9–1.9 | ---- | trace | trace | ---- |

For scientific names, see text.

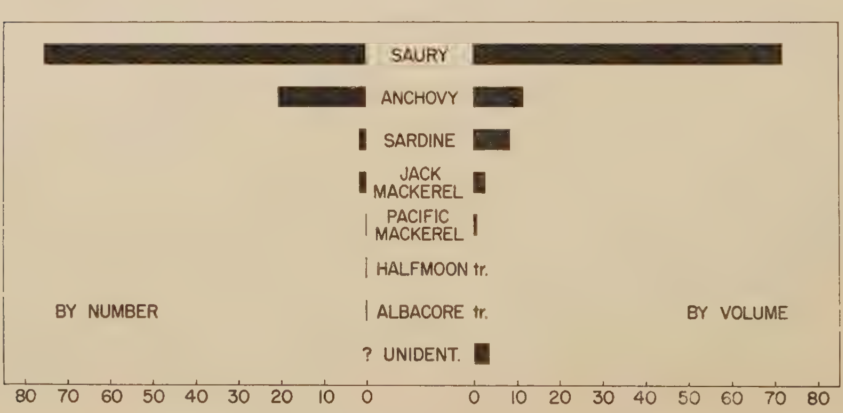

FIGURE 1. Percentage composition of fish food of 32 marlin

anchovy was definitely second in numbers (249, or about 21 percent of the fish eaten) and volume (2,362 cc., or about 12 percent).

Sardines, *Sardinops caerulea* (Girard), and jack mackerel, *Trachurus symmetricus* (Ayres), followed and were close in numbers (respectively 21 and 20), but the large sardines, which were mostly fresh and whole, much exceeded the more digested jack mackerel in volume (1,742 cc. versus 591 cc.). Two partly digested Pacific mackerel measured 153 cc. A large young halfmoon, about half complete, measured 6 cc. (young halfmoons long retain a surface-pelagic habitat). A single bone, a posttemporal, almost surely represented a small tuna or tuna-like fish, definitely not an albacore, almost surely a California bonito, *Sarda lineolata* (Girard), about one foot long.

The only other recognizable food item comprised six squid beaks, representing three to six individuals of at least two species.

In 19 stomachs of marlin caught during the first week of October, the percentage of stomachs containing each recognizable food item was:

Saury, 95 percent
Sardine, 37 percent
Anchovy, 32 percent
Jack Mackerel, 11 percent
Halfmoon, 5 percent

It is clear from this examination that the striped marlin feeds on fish of moderate size. Except for the one young halfmoon, *Medialuna californiensis* (Steindachner)—a deep-bodied fish—and the single small bonito, all fish that had been eaten by the marlin examined were half-grown to adult specimens of medium-sized species. No fish eaten, so far as could be determined, was less than three inches long. No trace was seen of larvae or very young juveniles. In this regard the striped marlin seems to contrast sharply with tuna, including albacore (McHugh, 1952). Nor were any of the fish eaten more than about one foot long. It is known, however, that large marlin are capable of eating large tuna, at least those caught on a line (June, 1951).

None of the fish eaten showed obvious signs of having been impaled, cut in two, slashed, or otherwise injured by the marlin's sword, though the marlins, like the swordfish, are said to stun their prey by striking or impaling them with their sword (Norman, 1938, p. 160; Gudger, 1940, p. 225).

No flyingfish were included in the food examined, though *Cypselurus californicus* (Cooper) was common in the region at the time the marlin were caught. Nor were any found in the marlin stomachs analyzed by Wallace and Wallace (1942) and by Morrow (1952). Flyingfish, however, are a favored bait for marlin and were listed as one of their food items by Norman (1938, p. 160).

Very similar results were obtained by Wallace and Wallace (1942) in the study of the food of the "white marlin, *Tetrapturus albidus* Poey" off Maryland and by Morrow (1952) in his work on the food of *M. mitsukurii* in New Zealand. Both found fishes predominating over squid, the only other food item of consequence. In the fish from Maryland, where sauries are rare or absent, the round herring, *Etrumeus sadina* (Mitchill) predominated. (In southern California the local round herring, *Etrumeus othonops* (Eigenmann) is extremely rare.) In New Zealand the local saury, identified by Morrow as *Scomberesox saurus* (Walbaum), constituted 74.1 percent of the food analyzed by number of individuals of all species eaten. We are grateful to James E. Morrow, Jr., of Yale University, for a copy of his paper, in press at the time of writing.

We find very little published information on the food of marlins. LaMonte and Marcy (1941, p. 18) wrote:

> Our examination of the stomach contents of Marlins has shown that their diet is much the same as that of the Swordfish. Where smaller fishes are plentiful, they are utilized as food; in Chile, where squid are plentiful, the Marlin and Swordfish stomachs were always full of partially digested squid.

And of the swordfish, *Xiphias gladius* Linnaeus, the same authors wrote (p. 7):

> The Swordfish feeds on smaller fishes, such as herring, mackerel, etc., and on squid. The absence or presence of the food supply, and, in turn, the absence or presence of the food supply of the herring, mackerel, etc., largely accounts for the variability in the runs from year to year.

Miss Francesca LaMonte of the American Museum of Natural History and the International Game Fish Association kindly provides some additional items on the food of marlins, as follows:

> In the striped marlins (*M. mitsukurii*) and also in the swordfish (*Xiphias*) I examined in Peru and Chile in 1940, there were only squid in the stomachs. Squid are thick there from surface to several feet down at night and evidently the marlins and swordfish had fed on them at night because those taken in the morning showed less digested squid than those taken in late afternoon, when usually only beaks and eyes were left. We got no blacks there that year.
>
> Dr. D. G. Maitland of Sydney, Australia, has recently written us as follows: "It may interest you to know that I have actually watched a pair of Black Marlin feeding upon Physalia—like huge Rainbow Trout taking flies, and absolutely ignoring a most tempting looking mackerel bait drifting in front of their noses."
>
> In notes from Bimini for blue marlin, I find that a blue weighing 420 lbs. caught July 8, 1937, had in its stomach a bonito weighing 5½ lbs. The bonito was doubled in the stomach, tail to head and practically whole; only its belly was opened a little. Nothing else was in the marlin's stomach.
>
> In several blues caught in 1949 and 1950 off Bimini there were small *Scomberomorus* partially digested; in one the skull and bones of a small grunt; in one some squid and a few fish bones; in one an almost undigested *Caranx latus* about 15″ long, and in one the bait—a bonefish.
>
> In Acapulco, Mexico, most of the few specimens taken of black, striped, and "silver" marlins had thrown the stomach contents; in all others, the contents were absolutely liquid and could not be identified.
>
> In no case have I ever seen anything that seemed to have been slashed by the spear or impaled upon it.

Our study suggests that the striped marlin in California feeds chiefly on the saury, a species that is seldom utilized here by fishermen. A few sauries have been experimentally packed at Monterey (in the scarcity of sardines), but there is no regular fishery in California for this abundant species, as there is in Japan. The other species that we find to be eaten by marlin near San Diego are all caught in the sport, commercial, or bait fisheries. The marlin is so highly prized, however, that no great concern will likely be felt over the fish it consumes or over its competition for food with other commercial or game fishes. It is highly improbable that enough marlin visit our coast, even in seasons of greatest abundance, to make any serious inroads on the numbers of the species that it feeds upon.

## REFERENCES

Clothier, Charles R.
1950. A key to some southern California fishes based on vertebral characters. Calif. Div. Fish and Game, Fish Bull. 79, p. 1-83, figs. 1-22, pls. 1-23.

Gudger, E. W.
1940. The alleged pugnacity of the swordfish and the spearfishes as shown by their attacks on vessels [a study of their behavior and structures which make these attacks possible]. Roy. Asiatic Soc. Bengal, Mem., vol. 12, no. 2, p. 215-315, figs. 1-22, pls. 3-9.

Hubbs. Carl L., and E. Ross Allen
1943. Fishes of Silver Springs, Florida. Fla. Acad. Sci., Proc., vol. 6, p. 110-130, figs. 1-4.

June, Fred C.
1951. Note on the feeding habits of the giant white marlin of the Pacific. Pac. Sci., vol. 5, no. 3, p. 287.

LaMonte, Francesca, and Donald E. Marcy
1941. Swordfish, sailfish, marlin, and spearfish. Internat. Game Fish Assoc., Ichthyol. Contribs., vol. 1, no. 2, p. 1-24, fig. 1, pls. 1-5.

McHugh, J. L.
1952. The food of albacore (Germo alalunga) off California and Baja California. Scripps Inst. Oceanog., Bull., vol. 6, no. 4, p. 161-172, figs. 1-4.

Morrow, James E.
1952. Food of the striped marlin, *Makaira mitsukurii*, from New Zealand. Copeia, no. 3, p. 143-145.

Norman, J. R.
1938. Giant fishes. Part I of Giant fishes whales and dolphins, by J. R. Norman and F. C. Fraser. New York, W. W. Norton and Co., 361 p., illus. (republished in 1949 by G. P. Putnam's Sons, New York, under the incomplete title, Field book of giant fishes).

Wallace, David H., and Elizabeth M. Wallace
1942. Observations on the feeding habits of the white marlin *Tetrapturus albidus* Poey. Maryland Dept. Res. and Educ., no. 50, p. 1-10, 1 fig.

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# THE EFFECT OF WINDS AND OCEAN CURRENTS ON THE ANNUAL VARIATION IN LATITUDE

By *Walter Munk and Gordon Groves*

University of California[1]

(Manuscript received 10 June 1952)

## ABSTRACT

An elliptical excursion (mean diameter 20 feet), described annually by the pole of instantaneous rotation
ver the earth's surface, has been deduced from precise astronomic observations of latitude. According to
effreys and Rosenhead, most of this excursion can be ascribed to the seasonal variation in the distribution
matter (air, water, snow and vegetable matter). The most important single factor is the gain, in winter,
air mass over the Asiatic continent, and the corresponding loss over the Atlantic and east Pacific oceans.
In this paper, it is shown that the effect of winds may be far from negligible. Here the important factor
the pressure against the Himalayas during the monsoon winds. Ocean currents account for only 1 per
nt of the excursion. It is suggested that the latitude observations, together with related astronomic
oservations concerning an annual change in the length of day, provide a promising method for measuring
rtain fundamental modes in the annual oscillation of the atmosphere.

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## ion

ll annual fluctuations have been reported
: components of the vector representing
velocity of the earth. The fluctuations in
l $y$-components (which determine the
he body of the earth, of the instantaneous
tion in the meridians of Greenwich and
sent a "wobble" of the earth; they are
m precise measurements of latitude.
; in the $z$ component[2] (through the mean
ire interpreted in terms of a slight seasonal
the length of the day. These have been
nore recently from precise measurements
.

auses fall into two categories: those due
n the tensor of inertia because of shifts in
ion of matter within the earth, ocean and
and those due to changes in the angular
of atmosphere and ocean (winds and

1915–16) has found the effect of changes
r of inertia to be of the right order of
o account for the observed changes in
egarding a possible effect of changes in
mentum, he writes: "If it should sub-
e found that there are large periodic
tive to the earth as a whole that do
nsiderable angular momentum, then these
be included in a more detailed treatment."

In the case of seasonal variations in the length of the day, it is found that the effect of winds is larger than that due to the tensor of inertia (Van den Dungen *et al.*, 1950; Mintz and Munk, 1951; Munk and Miller, 1950). This circumstance has led us to examine the effect of angular momentum on the wobble of the earth.

## 2. The Eulerian equations

Let $H_P = H_E + H_A$ be the angular momentum of the planet Earth, made up of the angular momentum $H_E$ of the solid earth and $H_A$ of the atmosphere. If no torque acts on the planet,

$$dH_E/dt = -\, dH_A/dt. \qquad (1)$$

On the other hand, we may wish to adopt the point of view that the atmosphere exerts a torque $L$ on the solid earth, so that

$$dH_E/dt = L. \qquad (2)$$

At present, (1) and (2) are merely two ways of saying the same thing. Yet, they imply different approaches to the problem that require different types of measurements.

Equations (1) and (2) refer to an absolute (nonrotating) coordinate system. The "absolute" derivative $d/dt$ can be transformed to a derivative $(\dot{\ })$ relative to a coordinate system fixed to the rotating earth, according to

$$d/dt = \boldsymbol{\omega} \times \;\; + (\dot{\ }),$$

where $\boldsymbol{\omega}(t)$ is the angular velocity of the wobbling

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iversity of California.

he Kimura $z$ component.

earth. Thus,

$$dH_E/dt = [\boldsymbol{\omega} \times \quad + (\dot{\ })] \int_E \rho \mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{r})\, dV$$

$$= \int_E \rho[r^2\dot{\boldsymbol{\omega}} - (\mathbf{r}\cdot\dot{\boldsymbol{\omega}})\mathbf{r} + (\mathbf{r}\cdot\boldsymbol{\omega})(\mathbf{r} \times \boldsymbol{\omega})]\, dV,$$

where the integral is taken over the whole volume of the solid earth. Here **r**, the vector from the earth's center to any point of the (rigid) earth, does not vary in time; but **ω** does, because of the wobble. Next,

$$dH_A/dt = [\boldsymbol{\omega} \times \quad + (\dot{\ })] \int_A \rho \mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{r} + \mathbf{v})\, dV$$

$$= \int_A \rho[(\mathbf{r}\cdot\boldsymbol{\omega})(\mathbf{r} \times \boldsymbol{\omega}) + 2\mathbf{r} \times (\boldsymbol{\omega} \times \mathbf{v}) + \mathbf{r} \times \dot{\mathbf{v}}]\, dV,$$

where the integral is taken over the atmosphere, and $\mathbf{v}$ designates motion relative to the earth (winds). Variations in $\rho$ have been neglected. Here **ω** has been taken as constant[3], but **r** varies with time, and $\dot{\mathbf{r}} = \mathbf{v}$. Finally,

$$L = \int \mathbf{r} \times \mathbf{s}\, dS, \qquad (3)$$

where $\mathbf{s}$ is the *stress* exerted by the atmosphere on the solid earth. The integral is to be evaluated over the entire surface.

For numerical calculations, we shall need to write (1) and (2) in scalar form. Let $\theta$ designate the co-latitude, $\phi$ the east longitude, and $\mathbf{v} = u\boldsymbol{\phi}_1 + v\boldsymbol{\theta}_1$ designate the wind vector, with the components $u$ from the west and $v$ from the north. We neglect the effect of vertical winds. For a Cartesian coordinate system fixed in the earth, let the $x$-axis intersect the equator at the meridian of Greenwich, the $y$-axis intersect the equator at 90°E, and the $z$-axis point to the mean position of the north pole. Let $a$ designate the radius, and $A, A, A(1 + 1/\tau), E, F, G$ the moments and products of inertia of the solid earth; $\tau$ is the number of sidereal days in the Newcomb period (434). The expression $1 + 1/\tau$ allows for the equatorial bulge. Then, equating $x$- and $y$-components in (1), we eventually obtain

$$\begin{aligned} l - (\tau/\omega)\dot{m} &= \lambda_i + \lambda_v + \lambda_a, \\ m + (\tau/\omega)\dot{l} &= \mu_i + \mu_v + \mu_a, \end{aligned} \qquad (4)$$

where

$$l = \omega_x/\omega, \quad m = \omega_y/\omega, \quad 1,$$

are the direction cosines of the earth's instantaneous axis of rotation, with $\omega \approx \omega_z$ designating the mean angular velocity of the earth.

The component equations (4) contain integrals on the right side. It is convenient to these into three parts, as shown. The term

$$\lambda_i = -\frac{\tau\kappa}{A} F = -\frac{\tau\kappa}{A} a^2 \int_A \rho \sin\theta \cos\theta \cos\phi$$

and a similar term[4] for $\mu_i$, are those investi Jeffreys. They incorporate the effects of slig ences, at various times of the year, in the pr *inertia* $E$ and $F$ due to the variable distrib mass over the earth's surface. The princi ponents are air, water, snow, and vegetable The coefficient $\kappa$ allows for the elastic yieldi earth under the pressure of superficial matter and $F$ are to be considered due only to this Rosenhead (1928) sets $\kappa$ equal to 0.6.

The term[4]

$$\lambda_v = -(2\tau a/A\omega)$$
$$\times \int_A \rho(u \cos\theta \cos\phi + v \cos^2\theta \sin\phi)$$

takes into account *velocity* relative to the earth and the term

$$\lambda_a = -(\tau a/A\omega^2) \int_A \rho(\dot{u} \cos\theta \sin\phi - \dot{v} \cos\phi)$$

*acceleration* relative to the earth. In this de we have neglected all products and squares quantities (see Jeffreys, 1915–16).

If one proceeds in a similar fashion from th point of view, (2) and (3) ultimately lead to

$$\begin{aligned} l - (\tau/\omega)\dot{m} &= \lambda_t, \\ m + (\tau/\omega)\dot{l} &= \mu_t, \end{aligned}$$

where

$$\lambda_t = -\frac{\tau}{A\omega^2} L_y$$

$$= -\frac{\tau a}{A\omega^2} \int (s_\theta \cos\phi - s_\phi \cos\theta \sin\phi)$$

and to a similar[4] expression for $\mu$. The integ be evaluated over the earth's surface.

There is some evidence that the fluid co earth does not fully participate in irregula rotation with periods as short as one year. not be able to take this possibility into accou extreme case that the core does not particip $A$ should pertain only to the earth's mantle, computed values of $\lambda$ and $\mu$ should accord increased by about 15 per cent over what in this study.

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[3] This means that, in computing the effect of atmospheric motion on the wobble of the earth, we neglect the effect of this wobble back onto the atmosphere.

[4] Expressions for $\mu$ can always be found from thos replacing $\phi$ by $\phi - \frac{1}{2}\pi$, hence by replacing $\cos\phi$ by $\sin\phi$ by $-\cos\phi$.

### on of momentum and torque approaches

uctive to consider first the earth wobble
ome simple, specified motion; for example,
ncer of mass $M$ standing on the Greenwich
some co-latitude $\theta_0$, moving her center of
small amount $b \sin \sigma t$ in an east-west
hen $u = \sigma b \cos \sigma t$, $\dot{u} = -\sigma^2 b \sin \sigma t$, and
ıducing the earth's wobble, according to
(7), are

$$- (\tau/A)a^2 M \sin \theta_0 \cos \theta_0 \cos \phi,$$

$$- 2(\tau/A)(\sigma/\omega)abM \cos \theta_0 \cos \sigma t,$$

$$- (\tau/A)(\sigma/\omega)^2 abM \cos \theta_0 \sin \sigma t,$$

$, = \lambda_a = 0$. Here $\phi = (b \sin \sigma t)/(a \sin \theta_0)$.
part of $\cos \phi$ is nearly $-\frac{1}{2}\phi^2$. The ratio
n the wobble induced by shift in mass
nduced by the motion is of the order
and not necessarily small. On the other
s of the order of $\sigma/\omega = 1/365$, and hence
annual motion.
sider the stresses induced. The normal
the earth's surface by virtue of her mass
considered as due partly to Newtonian
y the earth, partly as related to the
orce. The former is balanced exactly by
n of the earth by the dancer, according
third law. The latter gives

$$= M\omega^2 a \sin \theta_0 \cos \theta_0, \quad s_\phi = 0.$$

force, by virtue of her motion, yields

$$s_\theta = 2M\omega u \cos \theta_0, \quad s_\phi = 0,$$

celeration induces a stress $s_\theta = 0$, $s_\phi$

se three expressions for stress are sub-
(9), they lead to the above formulae for
, respectively. This merely shows that the
oach is consistent with our former ap-
s conclusion can be extended to a quite
on, not necessarily small.
ple is no longer trivial if we consider an
tion, for which we do not have the ana-
ion. We may proceed in two ways: (a)
g the position, velocity and acceleration
r, and computing $\lambda_i$, $\mu_i$, $\lambda_v$, $\mu_v$, $\lambda_a$ and $\mu_a$
(5), (6) and (7); (b) by placing the dancer
rm, and measuring by means of strain
force in excess of her weight at every
her motion. The latter method yields
$\mu_v + \mu_a$, but not $\lambda_i$ and $\mu_i$.
se of the atmosphere, it is customary to
s into components normal and tangential
The normal stress has the components

$$a \sin \theta \cos \theta)/g, \quad s_\phi'' = 0, \quad s_r'' \approx - p_s,$$

where $p_s$ is the (hydrostatic) atmospheric pressure at the surface. Substituting into (9) and allowing for elastic yield, we have

$$\lambda_t'' = - (\tau \kappa a^2/Ag) \int p_s \sin \theta \cos \theta \cos \phi \, dS. \quad (10)$$

From the point of view of angular momentum, we may regard the surface pressure as a measure of the overlying air mass, according to $p_s \approx g \int_a^\infty \rho \, dr$. Substitution of this into (5) also leads to (10). Hence $\lambda_i = \lambda_t''$, *i.e.*, the effect of the normal stress corresponds to that of the inertial terms. This means that the effect of the tangential stress (components $s_\theta'$, and $s_\phi'$) corresponds to the remaining terms,

$$\lambda_t' = \lambda_v + \lambda_a, \quad \mu_t' = \mu_v + \mu_a.$$

The effect of winds can therefore be found in two ways: (a) by evaluation of $\lambda_v$, $\mu_v$, $\lambda_a$ and $\mu_a$ from a (supposedly) known variation of wind and density throughout the atmosphere (section 6, below); (b) by evaluation of $\lambda_t'$ and $\mu_t'$ from the (supposedly) given tangential stress over the surface (section 7, below). Henceforth, we shall neglect the acceleration terms.

The tangential stress arises, aside from molecular stress, from slight pressure differences on the windward and lee sides of obstacles (blades of grass, waves, houses, mountains). It equals $p_s \nabla \eta$, where $p_s$ is the surface pressure, and $\eta$ is the elevation above sea level. In practice, it is convenient to consider separately the stresses against major mountain-chains (derived from measurements of pressure at weather stations on both sides of the mountains), and the "skin friction" against smaller obstacles (derived from surface winds by statistical considerations).

## 4. Astronomic observations

From astronomic observations, one can determine the coefficients in

$$l = l_c \cos \Theta + l_s \sin \Theta, \quad m = m_c \cos \Theta + m_s \sin \Theta,$$

where $\Theta$, the sun's longitude, increases from 0 on 21 March to $2\pi$ on 21 March of the following year. The coefficients are 0.1 sec at most. For comparison, 0.01 sec or $4.85 \times 10^{-8}$ rad corresponds to 1.01 ft of actual displacement of the pole of instantaneous rotation on the surface of the earth. It follows from (4) that

$$\lambda = (l_c - m_s \mathrm{T}) \cos \Theta + (l_s + m_c \mathrm{T}) \sin \Theta,$$

$$\mu = (m_c + l_s \mathrm{T}) \cos \Theta + (m_s - l_c \mathrm{T}) \sin \Theta,$$

where $\mathrm{T} = \tau\sigma/\omega = 1.20$ is the Newcomb period in years, and $\sigma$ is the annual frequency. From a summary of astronomic observations covering the first half of the 20th century, Jeffreys[5] finds

$$\begin{aligned} \lambda &= -0.013 \cos \Theta + 0.000 \sin \Theta, \\ \mu &= 0.007 \cos \Theta + 0.044 \sin \Theta, \end{aligned} \qquad (11)$$

where the coefficients are in seconds and have a standard error of 0.011. These values are to be compared with those obtained from meteorologic considerations.

## 5. The inertial terms

The inertial terms are the ones investigated by Jeffreys (1915–16) and Rosenhead (1929). The most important part is due to shifts in air masses[6], and these can be computed from variation in station-level (not sea-level) pressures $p_s$, since $\int_a^\infty \rho \, dr \approx p_s/g$. Equation (5) becomes

$$\lambda_i = -(\tau \kappa a^4/Ag) \times \int_0^{2\pi} \int_0^{\pi} p_s \sin^2 \theta \cos \theta \cos \phi \, d\theta \, d\phi. \qquad (12)$$

For comparison with our later results, we shall adopt a slightly different procedure than Jeffreys'. Suppose the station-level pressure is expanded into a series of tesseral surface harmonics (Schmidt, 1935),

$$p_s = \sum_{n=0}^{N} \sum_{m=0}^{n} (C_n^m \cos m\phi + D_n^m \sin m\phi) P_n^m(\theta),$$

where $P_n^m(\theta)$ are seminormalized associated spherical harmonics for integral order, defined by

$$P_n^m(\theta) = \left[\frac{2(n-m)!}{(n+m)!}\right]^{\frac{1}{2}} \left[\frac{(2n)!}{2^n n!\,(n-m)!}\right] \sin^m \theta \Bigg[ \cos^{n-m} \theta - \frac{(n-m)(n-m-1)}{2(2n-1)} \cos^{n-m-2} \theta + \frac{(n-m)(n-m-1)(n-m-2)(n-m-3)}{2 \times 4(2n-1)(2n-3)} \times \cos^{n-m-4} \theta - \cdots \Bigg]$$

for $m > 0$, and

$$P_n^0(\theta) = \left[\frac{(2n)!}{2^n n!\, n!}\right] \left[ \cos^n \theta - \frac{n(n-1)}{2(2n-1)} \cos^{n-2} \theta + \frac{n(n-1)(n-2)(n-3)}{2 \times 4(2n-1)(2n-3)} \cos^{n-4} \theta - \cdots \right].$$

The coefficients $C$ and $D$ are functions of $\Theta$. We find that only the term for which $m = 1$, $n = 2$, contributes to the integral in (12). This gives

$$\begin{aligned} \lambda_i &= -1.451(\tau \kappa a^4/Ag) C_2^1, \\ \mu_i &= -1.451(\tau \kappa a^4/Ag) D_2^1. \end{aligned}$$

Let us suppose, for the moment, that al observed variation in latitude is due entirely in air mass[6]. Then use of the numerical value with $\kappa = 0.6$, gives (in millibars)

$$p_s = [(0.7 \cos \Theta + 0.0 \sin \Theta) \cos \phi - (0.4 \cos \Theta + 2.3 \sin \Theta) \sin$$

for the simplest pressure-pattern to achi observed wobble (fig. 1). When this is com observed conditions, its similarity to the c the Asiatic continent becomes at once appar northwestern quadrant, centered over Am dominated in summer by the east Pacific and high-pressure areas, and in winter by the Aleu Iceland low pressures. These features, which h shadow a relatively weak opposite effect American continent itself, are again in agreem the required pattern. In the southern hem such obvious agreement is lacking. The effect is therefore the loss in winter of air m the Atlantic and east Pacific oceans, and th sponding gain over the Asiatic continent, pointed out by Spitaler (1901).

The magnitude of the required effect, a change of 4.6 mb at the very most, does not all excessive. In fact, local changes over Asia 20 mb. However, calculations by Rosenhea indicate that the shifts in air mass account two-thirds of the observed effect, and are not the desired phase.

## 6. Winds, angular momentum approach

*The atmosphere as a solid shell.*—Cons atmosphere as a rotating solid shell with it pole" at $\theta_A$, $\phi_A$, and with angular speed $\omega_A$ re the earth. It can be shown that, for this leads to

$$\lambda_v = \frac{8\pi}{3} \frac{\tau a^4 p_s}{Ag\omega} \omega_A \sin \theta_A \cos \phi_A.$$

For future reference, we note that the portio shell contained between 20°N and 20°S co only

$$\frac{\cos^3 110° - \cos^3 70°}{\cos^3 180° - \cos^3 0°} \lambda_v = 0.04 \lambda_v,$$

or 4 per cent of the total effect.

Let us suppose, for the moment, that a observed variation in latitude is due to this s gives

$$a\omega_A \sin \theta_A = 13.4 \text{ cm/sec}, \qquad \Theta = 80$$

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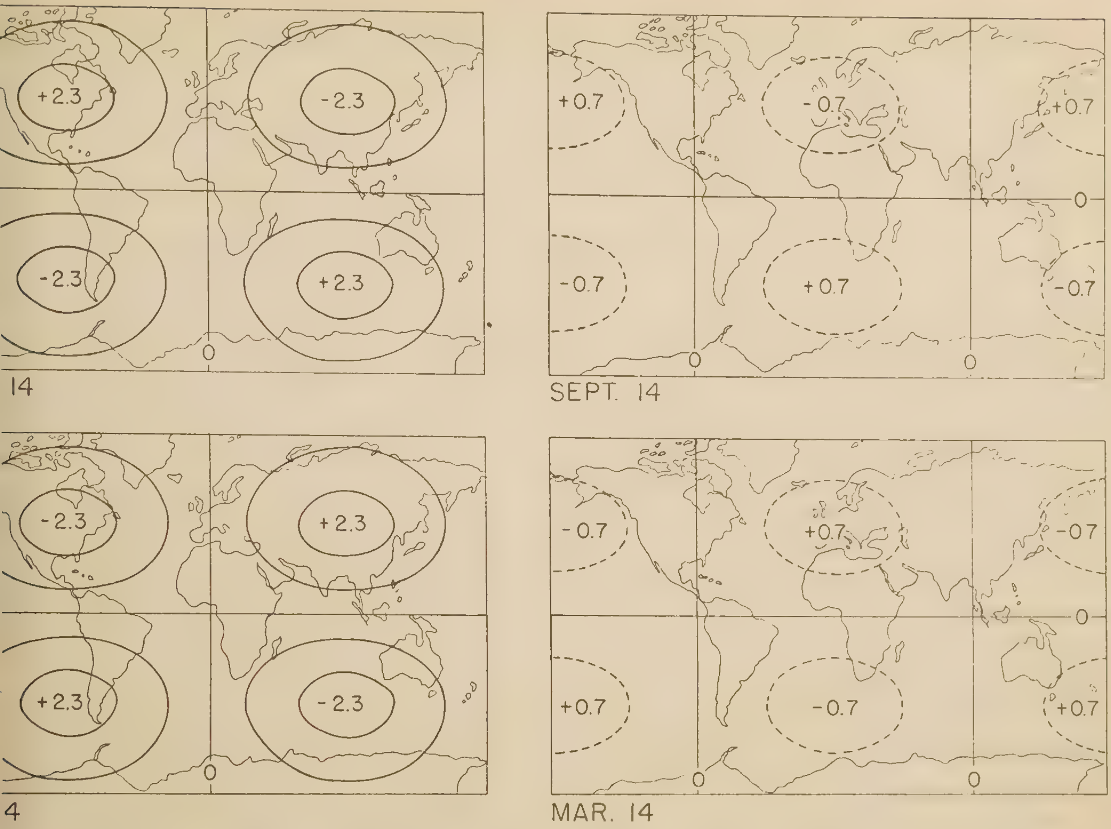
[5] Prof. Jeffreys has kindly made these revised values available to us. They are to be published in the third edition of *The earth.*

[6] The effect of the actual motion, which must accompany such changes in distribution, can be neglected. The least motion required to accomplish the observed variation in the pressure pattern is altogether negligible compared to the observed winds.



-pressure variations (millibars) which could account for all of observed wobble. Dates are those for which pressure ariations reach maximum or minimum values. Zero isobars in left figures are at 3°E (not zero) longitude.

nitude and time of the maximum winds.
e north pole of the atmospheric shell
ed at $\theta_A = 20$ deg over the northwest
Siberia. Then the maximum velocity-
$\omega_A a$, is 78 cm/sec between 14 June and 14
This applies only to the "equator" of the
c shell. At other places, the maximum
erence will be less; on the average, it equals
0 cm/sec. These values are so small
o observed seasonal wind-variations that
ect the effect of winds on the wobble to be
out barely detectable from available data.

*Geostrophic winds.*—We may define a vertically averaged wind by

$$\int_a^\infty \rho v\, dr = -g^{-1}\int_{p_s}^0 v\, dp = \frac{\bar{v}p_s}{g},$$

where $p_s$ is the atmospheric pressure at the ground. On the average, $\bar{v}$ is the wind at the 500-mb level. Except for the equatorial region, we can compute $\bar{v}$ from the geostrophic law,

$$\bar{u} = \frac{g}{2a\omega\cos\theta}\frac{\partial h}{\partial\theta}, \quad \bar{v} = -\frac{g}{2a\omega\cos\theta\sin\theta}\frac{\partial h}{\partial\phi},$$

TABLE 1. Effect of geostrophic winds on the annual variation in latitude.

| $G_n^1$ (cm) | | | | $\lambda_v$ (sec) | | | |
|---|---|---|---|---|---|---|---|
| | | Zonal | | Meridional | | Total | |
| cos Θ | sin Θ | cos Θ | sin Θ | cos Θ | sin Θ | cos Θ | sin Θ |
| 536 | −1145 | .0009 | −.0019 | −.0160 | .0341 | −.0151 | .0322 |
| 649 | −1872 | .0301 | −.0868 | −.0119 | .0344 | .0182 | −.0524 |
| −972 | − 483 | .0074 | .0037 | .0101 | .0050 | .0175 | .0087 |
| −209 | 759 | −.0029 | .0105 | .0021 | −.0075 | −.0008 | .0030 |
| | | .0355 | −.0745 | −.0157 | .0660 | .0198 | −.0085 |
| $H_n^1$ (cm) | | | | $\mu_v$ (sec) | | | |
| | | Zonal | | Meridional | | Total | |
| 1354 | − 715 | .0023 | −.0012 | −.0403 | .0213 | −.0380 | .0201 |
| 147 | 1572 | .0068 | .0729 | −.0027 | −.0289 | .0041 | .0440 |
| − 498 | 640 | .0038 | −.0049 | .0052 | −.0067 | .0090 | −.0116 |
| −2077 | − 144 | −.0287 | −.0020 | .0205 | .0014 | −.0082 | −.0006 |
| | | −.0158 | .0648 | −.0173 | −.0129 | −.0331 | .0519 |

where $h$ is the elevation of that particular pressure surface ($\approx$ 500 mb) along which the wind equals $\bar{v}$. Equation (6) now becomes

$$\lambda_v = -\frac{\tau a^2 p_s}{A\omega^2}\int_0^{2\pi}\int_0^{\pi}\left(\frac{\partial h}{\partial\theta}\sin\theta\cos\phi - \frac{\partial h}{\partial\phi}\cos\theta\sin\phi\right)d\theta\,d\phi. \quad (15)$$

We can now compute $\lambda_v$ and $\mu_v$ from charts of $h(\theta, \phi)$, just as previously we computed $\lambda_i$ and $\mu_i$ from charts of $p_s(\theta, \phi)$. The present calculation is, however, less reliable because (a) the 500-mb winds are a much less accurate representation of the movement of the atmosphere as a whole than the surface pressures are of the mass of the atmosphere, and (b) the elevation of the 500-mb surface is known less accurately than the surface pressures. Suppose $h$ is expanded in tesseral harmonics,

$$h = \sum_{n=0}^{N}\sum_{m=0}^{n}(G_n^m\cos m\phi + H_n^m\sin m\phi)\,P_n^m(\theta).$$

Then only terms for which $m = 1$ contribute to (15), which becomes

$$\lambda_v = -\frac{\tau a^2 p_s \pi}{2A\omega^2}\sum_{n=1}^{N}G_n^1\left[\sqrt{2n(n+1)}\int P_n^0(\theta)\sin\theta\,d\theta - \sqrt{(n+2)(n-1)}\int P_n^2(\theta)\sin\theta\,d\theta + 2\int P_n^1(\theta)\cos\theta\,d\theta\right]. \quad (16)$$

The first two terms follow from zonal winds, the third from meridional winds. The integrals are to be evaluated over the region for which the geostrophic law applies. This excludes an equatorial strip. If this strip is symmetrical with respect to the equator, only even values of $n$ contribute to $\lambda_v$; in particular, if we exclude the region between 20°N and 20°S latitudes ($\theta$ from 70° to 110°),

$$\lambda_v = -\frac{\tau a^2 p_s \pi}{A\omega^2}[(-0.062 + 1.109)G_2^1 + (-1.727 + 0.685)G_4^1 + (0.283 + 0.389)G_6^1 + (-0.514 + 0.367)G_8^1 + \cdots], \quad (17)$$

and a similar expression for $\mu_v$ in which the $G$'s are replaced by $H$'s. The first number in each parenthesis results from zonal winds, the second number from meridional winds.

If we retain only the first term[7] of the series, a comparison of (13) and (17) shows that the ratio of the effect of winds to that of inertia is given

$$\frac{\lambda_v}{\lambda_i} = \frac{1.047\,\pi}{1.451\,\kappa}\,\frac{p_s}{a^2\omega^2\rho_{500}}\,\frac{(C_2^1)_{500}}{(C_2^1)_s} \approx 2.55\,\frac{(C_2^1}{(C}$$

where $\rho_{500}$ is the mean density at 500 m $= \rho_{500}gG_2^1$ is the pressure component at about $(C_2^1)_s$ is the corresponding surface-press ponent. Suppose the geostrophic winds are t for all of the observed wobble. Then the winds, averaged vertically, are those tha result from the pattern in fig. 1, provided th are interpreted as isobars at an elevation o km and the isoline interval is changed fr 1/2.55 mb. The magnitude of the required change, 4.6/2.55 or 1.8 mb, is so small th hardly be detected from present data. Th substantially with the conclusion for the soli

We have, nevertheless, attempted to eva terms from charts of the elevation of the surface for four seasons prepared by Bro (1950). The method is given below in the the results in table 1. Errors in the comp scheme are smaller than those inherent in The terms do not converge as rapidly wit desirable. The totals for $\lambda_v$ are made up of tw and two negative numbers, and the degree of tion makes the totals quite unreliable. The cancellation for $\mu_v$. All that can be said is computed values resulting from the geostrop are of the same order of magnitude as the as observations. .

*Equatorial winds.*—We do not believe that data are sufficiently accurate or complete the evaluation of the integrals. There are, several reasons why the contribution by winds can be expected to be less important contribution by winds elsewhere. In the first trade winds vary less with the seasons tha westerlies; in the second place, winds at th do not contribute to $\lambda_v$ and $\mu_v$. For the "so atmosphere, it was shown [equation (14)] shell between 20°N and 20°S contributes o cent of the total effect.

## 7. Winds, stress approach

If the components of surface stress are ex tesseral harmonics according to

$$s_\phi = \sum_{n=0}^{N}\sum_{m=0}^{n}(C_n^m\cos m\phi + D_n^m\sin m\phi)\,P$$

$$s_\theta = \sum_{n=0}^{N}\sum_{m=0}^{n}(C_n'^m\cos m\phi + D_n'^m\sin m\phi)$$

it is found that only the components $C_2^1$, $C_4^1$

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[7] For terms of higher order, $C_4^1$, $C_6^1$, $\cdots$, the winds contribute to the wobble, but the shifts in air mass do not.

d $C'^1_1, C'^1_3, \cdots, D'^1_1, D'^1_3, \cdots$, contribute to he formulae are

$$\frac{\pi}{2}(0.680\, D^1_2 + 0.155\, D^1_4 + 0.070\, D^1_6 + 0.040\, D^1_8 + \cdots), \qquad (18)$$

$$\frac{a^3\pi}{A\omega^2}(1.571\, C'^1_1 + 0.241\, C'^1_3 + 0.095\, C'^1_5 + 0.051\, C'^1_7 + \cdots),$$

ects of the meridional and zonal com- spectively. The corresponding expressions 1 $(\mu_t)_\theta$ are found by replacing $+ D$ by $- C$, y $+ D'$.

ain only the first term in each series, and f the observed wobble first to zonal stresses to meridional stresses only, the required outions are (in dynes/cm²)

$$.5 \cos \Theta + 3.3 \sin \Theta) \cos \phi + (1.0 \cos \Theta + 0.0 \sin \Theta) \sin \phi] \sin 2\theta,$$

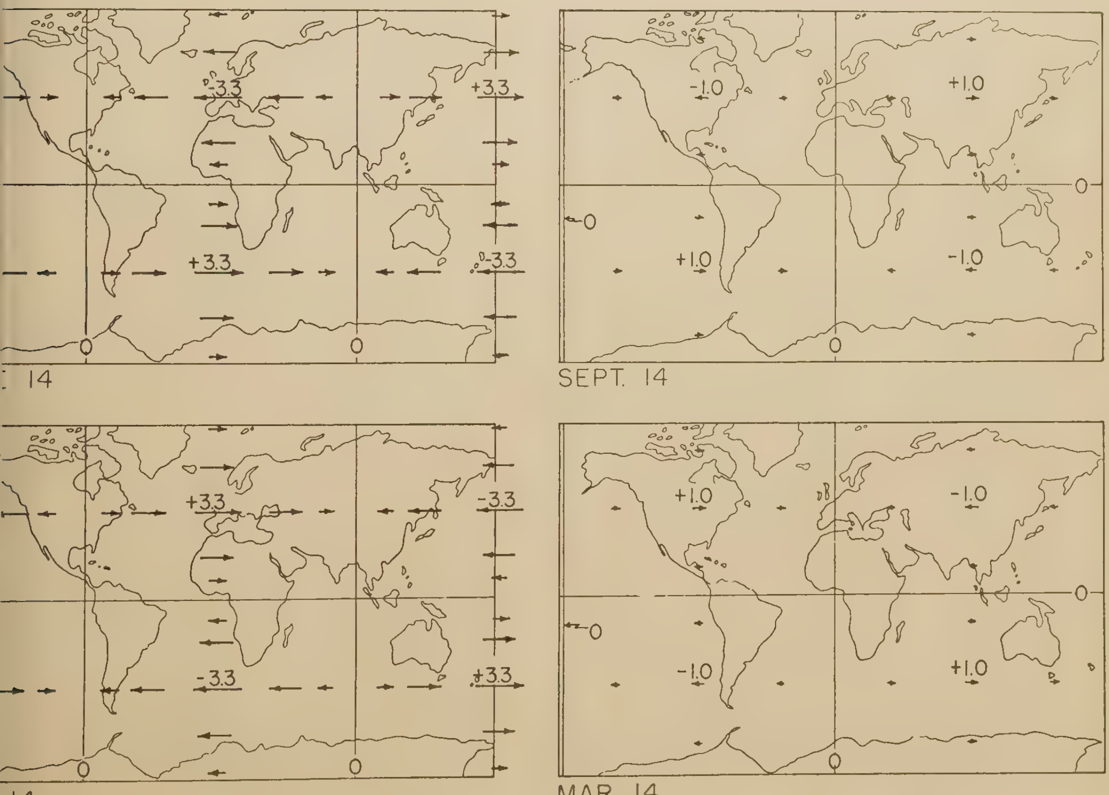
$$os\ \Theta + 0.0 \sin \Theta) \cos \phi - (0.3 \cos \Theta + 1.6 \sin \Theta) \sin \phi] \sin \theta,$$

, as shown in figs. 2 and 3. These may be he simplest stress-patterns to achieve the bble.

From general consideration of atmospheric circulation, we know that stresses of the order of 1 dy/cm² are representative over large portions of the earth's surface. Mintz (1951) finds that the zonal stress between 35°N and 90°N averages 1 dy/cm², of which one third to one half is due to skin friction, the remaining part to the mountain effect. Variations up to 6.6 dy/cm² in the zonal stress, as shown in fig. 2, seem rather large. Furthermore, the zonal-stress pattern does not resemble the observed pattern. The meridional stresses, however, are in phase with the monsoon winds, and their magnitude is about what would be expected.

In section 6 we had noted that annual changes in wind of less than 1 m/sec, or in pressure of only a few millibars, could account for all of the observed wobble; yet these values were so small that they were barely over the threshold of detectability. Here we find that the corresponding stress variation is by a few dynes per square centimeter, a value above the threshold of detectability. From these elementary considerations, we may conclude that the present torque method is inherently more accurate than the momentum method of section 6, and that the meridional wind-stress can be expected to contribute towards the observed wobble.

*Stress over oceans.*—Tables of wind stress over the North Pacific (north of 5°S) and the North and



14

SEPT. 14

14

MAR. 14

ıal variation in surface stress from zonal winds, which could account for all of observed wobble. Dates are those for riations reach maximum or minimum values. Length of arrows is proportional to stress. Values (dynes/cm²) of largest are indicated. Solid lines represent zero stress.

TABLE 2. Effect of wind stress over oceans.

| | $\lambda_t$ (sec) | | $\mu_t$ (sec) | |
|---|---|---|---|---|
| | cos Θ | sin Θ | cos Θ | sin Θ |
| Pacific Ocean: | | | | |
| zonal stress | .00012 | −.00005 | .00020 | −.00059 |
| meridional stress | .00080 | −.00067 | .00022 | .00062 |
| Atlantic Ocean: | | | | |
| zonal stress | −.00020 | .00031 | −.00019 | .00042 |
| meridional stress | −.00070 | .00035 | .00051 | −.00054 |

Central Atlantic (north of 20°S), for each month and 5-deg quadrangle, have been prepared at the Scripps Institution of Oceanography.[8] We estimate that the probable error does not exceed 25 per cent. With use of these stress tables, values of $\lambda_t$ and $\mu_t$ have been computed according to (9). The results are given in table 2. The amplitudes are 0.001 sec at most, and are therefore small relative to the observed values.

Actually these stresses are not transmitted directly to the solid earth, but only through the medium of the ocean currents. In section 8, below, an evaluation of the effect of ocean currents leads to the same order of magnitude.

*The mountain effect.*—We shall consider only the American continent and the Himalayas. The mountain effect over the American continent is due largely to pressure against the Rocky Mountains and the Sierra Nevadas. It has been shown by Mintz (1951) that we shall not be far from wrong if we consider only a wall, 3 km high, extending along 110°W between 30°N and 60°N, with a difference in pressure against its western face minus pressure against its eastern face in January exceeding that in July by 3.5 mb. This yields, approximately, in seconds,

$$\lambda_t = 0.002 \sin \Theta, \qquad \mu_t = -\ 0.001 \sin \Theta,$$

for the mountain effect over America. For the Himalayas, any dependable (station level) pressure-variations are lacking but the following estimate does not seem excessive. Suppose we consider the pressure against a vertical wall along 30°N, 2 km high between 40°E and 70°E, and 4 km high between 70°E and 100°E. The difference in pressure against the northern face minus the pressure against the southern face in January exceeds that in July by 15 mb. This gives, in seconds,

$$\lambda_t = 0.004 \sin \Theta, \quad \mu_t = 0.015 \sin \Theta,$$

for the mountain effect against the Himalayas. We note that this is very roughly in phase with the observed effect [equation (11)], and has about one third the observed amplitude.

## 8. Ocean currents

*Angular-momentum approach.*—The esse
ments of oceanic circulation are: (a) the
circumpolar current, which is largely a zona
(b) the equatorial circulation; (c) the subtro
subpolar gyres in the "confined" basins of t
Atlantic, North Pacific, South Atlantic, Sou
and Indian Oceans. A discussion of these fea
be found in Munk (1949) and Munk an
(1951).

First we note that uniform zonal motion a
the earth, and motion at the equator, do
tribute to $\lambda_v$ and $\mu_v$. Accordingly, we neglect
(a) and (b). This leaves the subtropical and
gyres in the five basins. By far the most imp
the subtropical gyres of the North Atlantic,
the Gulf Stream system, and of the Nort
including the Kuroshio systems. We shall
these first.

The effect on the earth's wobble of the r
flowing Gulf Stream alone is to a large ext
pensated by an equal southward flow of wat
eastern side of the Atlantic. We must
consider the entire effect of any gyre at one t
can be done by expressing the vertically i
mass-transport in terms of a stream fu
according to

$$\int \rho u \, dr = a^{-1} \, \partial\psi/\partial\theta,$$

$$\int \rho v \, dr = -\ (a \sin \theta)^{-1} \, \partial\psi/\partial\phi,$$

with the integration carried out from sea
sea surface. In terms of this function,

$$\lambda_v = -\frac{2\tau a^2}{A\omega} \int_{\phi_1}^{\phi_2} \int_{\theta_1}^{\theta_2} \left( \frac{\partial\psi}{\partial\theta} \sin\theta \cos\theta \cos\phi \right.$$

$$\left. - \frac{\partial\psi}{\partial\phi} \cos^2\theta \sin\phi \right) d\theta$$

The stream function can be expressed b
1949)

$$\psi = \psi_0 \sin \left( \pi \frac{\theta - \theta_1}{\theta_2 - \theta_1} \right) f(\phi),$$

where $f(\phi)$ rises almost abruptly from 0 to
western boundary $\phi_1$, and decreases linearly
the eastern boundary $\phi_2$. We may visualize t
tion, bounded by co-latitudes $\theta_1$ and $\theta_2$, and
$\phi_1$ and $\phi_2$, rotating clockwise about a cen
far towards the western side of the basin.
transport across any radial line from th
point to the border equals $\psi_0$. For the G
or the Kuroshio, $\psi_0 = 60 \times 10^{12}$ g/sec.
tematic observations at fixed stations thro

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[8] *The field of mean wind stress over the North Pacific Ocean; The mean wind stress over the Atlantic Ocean.* Oceanographic Reports Nos. 14 and 21 (unpublished).

3. The effect of the ocean circulation in the subtropical gyres.

| Co-latitudes (deg) $\theta_1$ | $\theta_2$ | Longitudes (deg E) $\phi_1$ | $\phi_2$ | $\lambda_v$ (sec) | $\mu_v$ (sec) |
|---|---|---|---|---|---|
| 45 | 75 | 285 | 345 | $-.0005 \cos \Theta$ | $+.0008 \cos \Theta$ |
| 45 | 75 | 130 | 230 | $+.0014 \cos \Theta$ | $-.0004 \cos \Theta$ |
| 105 | 135 | 035 | 115 | $-.0002 \cos \Theta$ | $-.0004 \cos \Theta$ |

rdly available, we depend largely on the
lence of tide gauges for an estimate of the
ation. In this manner, Iselin (1940) finds
rt in spring to be 20 per cent larger than
rt in the fall. Compilation of ships' logs
1951) supports Iselin's calculations. The
t of $\psi_0$ is $\Delta\psi_0 = 6 \times 10^{12} \cos \Theta$ g/sec. For
expression of the stream function, the
leads to

$$\frac{\psi_0}{}\left[\beta - \frac{\beta}{2(1-4\beta^2)}(\cos 2\theta_2 + \cos 2\theta_1)\right] \times \left[\frac{\cos\phi_2 - \cos\phi_1}{\phi_2 - \phi_1} + \sin\phi_1\right], \quad (21)$$

$\theta_2 - \theta_1)/\pi$.
l values are given in table 3. The first
rtain to the subtropical gyres of the North
d North Pacific. In addition, we must
subpolar gyres of the northern hemisphere
tropical gyres of the southern hemisphere
tlantic and Pacific. With regard to the
res, we note that the Labrador Current is
hase with the Gulf Stream, but opposite in
similar relation holds between Oyashio
io in the Pacific. The subpolar gyres will
*duce* the above values somewhat. With
e subtropical gyres of the southern oceans,
ıt the Brazil current is both opposite in
pposite in direction to the Gulf Stream,
the East Australian Current and the
These gyres will therefore *increase* the
s. There is, then, some cancellation. In
the circulation in these gyres amounts to
per cent of the circulation in the sub-
es of the northern hemisphere. We shall
ke the first two lines of table 3 as repre-
the entire Atlantic and Pacific Oceans.
es only the Indian Ocean. There the
rent corresponds to the Gulf Stream, but
-third its transport. The annual variation
at Kenya and Tanganyika is also about
that at Cape Hatteras. Phase and direc-
h opposite to those in the Gulf Stream.
stimate is, then, $\Delta\psi_0 = 2 \times 10^{12} \cos \Theta$
leads to the values in table 3.
ison of these values with the observed

values [equation (11)] indicates that the circulation in the Pacific Ocean alone accounts for 10 per cent of the magnitude in $\lambda$, but for only three per cent of the total observed wobble. There is, however, a good deal of cancellation between the three oceans, and the net result is less, and not reliable.

*Stress approach.*—The stress applied by the winds on the ocean surface is balanced largely by friction against the western boundary of the ocean basin. We can check the order of magnitude of the preceding calculation in the following manner. The western boundary is replaced by a vertical wall extending from the surface to some depth (1000 m) where the currents nearly vanish, and extending from $\theta_1$ to $\theta_2$ in a north-south direction. We now write for $f(\phi)$ in (20),

$$f(\phi) = -\frac{2}{\sqrt{3}} e^{-\frac{1}{2}k\xi} \cos\left(\frac{\sqrt{3}}{2}k\xi - \frac{\pi}{6}\right) + 1,$$

where $\xi = a(\phi - \phi_1)\sin\theta$ is the distance from the wall, and $k$ is the "wave number" of the Gulf Stream [Munk, 1950, equation (20)]. Then $s_\theta = \rho K(\partial v/\partial\xi)_{\xi=0}$ is the force per unit area, and $K(\partial^2\psi/\partial\xi^2)_{\xi=0}$ is the force per unit length of wall, $K$ being the (kinematic) eddy viscosity. The variable part of the force against the entire wall becomes

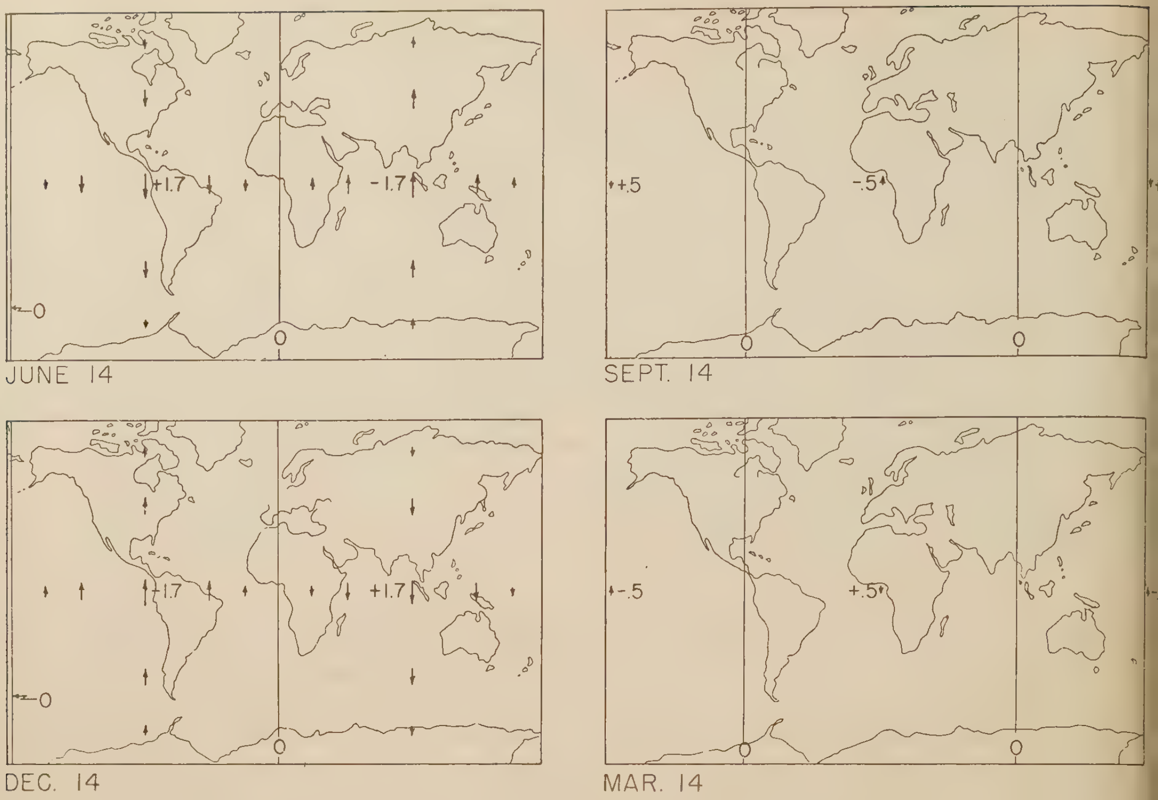
$$K\int_{\theta_1}^{\theta_2}\left(\frac{\partial^2\,\Delta\psi}{\partial\xi^2}\right)_{\xi=0} a\,d\theta = \frac{2}{\pi}(\theta_2 - \theta_1)k^2 K\,\Delta\psi_0.$$

Using the previous values for $\Delta\psi_0$, $\theta_1$ and $\theta_2$, and setting $k = 2 \times 10^{-7}$ cm$^{-1}$, $K = 2.5 \times 10^7$ cm$^2$/sec (Munk and Carrier, 1950), we find, upon substitution into (9), values of $\lambda_t$ and $\mu_t$ of the order of 0.001 sec, in agreement with our previous calculations.

## 9. Discussion and conclusions

Since the turn of the century, an annual motion of the axis of instantaneous rotation within the body of the earth has been deduced from measurements of latitude at observatories. With respect to this annual component, the north pole of instantaneous rotation describes nearly an ellipse. In September it is displaced, relative to its mean position, by 10 ft towards Greenland; in December by 8 ft towards Central Asia; *etc.* From the astronomic observations, the required *forcing function* with the components $\lambda$, $\mu$ has been computed by Jeffreys (table 4, line 1).

The problem is to account for this function in terms of happenings on the earth. It is convenient to treat separately the effects of (1) a variable distribution of matter over the earth and (2) a variable motion relative to the earth. The former involves integrals of $p_s(\theta, \phi, \Theta)$, the latter integrals of $\rho\bar{v}(\theta, \phi, \Theta)$, where $p_s$ is surface pressure, $\rho$ density, $v$ relative velocity (the bar denotes a vertical average), $\theta$ co-latitude, $\phi$ longitude, and $\Theta$ is the time of year.



JUNE 14 SEPT. 14

DEC. 14 MAR. 14

FIG. 3. Annual variation in surface stress for meridional winds. (Length and scale of stress arrows same as in fig. 2.)

In the evaluation of such integrals from meteorological data, our chief concern lies with the accuracy, even the reality, of the numerical results. Rather than to confine ourselves to somewhat inaccessible numerical compilations, we have therefore followed the procedure of first inquiring as to the simplest meteorological patterns that could account for the observed wobble. From an inspection of these patterns, the reader can tell whether they are reasonably distributed in time and geographical location, whether the required magnitudes are plausible, and if so, whether they are detectable from data now available.

Fig. 1 shows the simplest surface-pressure
consistent with the assumption that *all* of the ob
wobble is brought about by seasonal shifts in ai
A winter maximum of 2.3 mb over Asia does n
unreasonable. Next, suppose the observed wo
due entirely to winds. The prerequisite pattern
presented either by (2a) the seasonal distribu
momentum throughout the atmosphere, or (2
seasonal wind-stress (skin friction and mountain
over the earth's surface. If in the former c
confine ourselves to geostrophic winds betwee
and 20°N, 20°S and 90°S, the associated pr

TABLE 4. Summary of calculations.

| | $\lambda$ (sec) | | $\mu$ (sec) |
|---|---|---|---|
| | cos $\Theta$ | sin $\Theta$ | cos $\Theta$ |
| Astronomic observations | −.013 | .000 | .007 |
| 1. Distribution of matter (according to Jeffreys,[6] with $\kappa = 0.696$): | | | |
| Atmosphere | −.001 | .007 | −.005 |
| Snow | −.017 | .012 | −.009 |
| Vegetable matter | .001 | −.002 | .002 |
| Total | −.017 | .017 | −.012 |
| 2. Motion relative to the earth: | | | |
| 2a. *Angular-momentum approach* | | | |
| Winds (section 6) | .020 | −.009 | −.033 |
| Ocean currents (section 8) | .001 | .000 | .000 |
| 2b. *Torque approach* (*section 7*) | | | |
| Skin friction over N. Pacific | .001 | −.001 | .000 |
| N. Atlantic | .001 | .001 | .000 |
| Mountain effect, Rocky Mts. | — | .002 | — |
| Himalayas | — | .004 | — |

the elevation ($\approx$ 6 km) at which the wind in value is again given by fig. 1, provided interval is reduced by a factor of 2.5. The nplitude in the annual pressure-variation /2.5 $\approx$ 1 mb. The corresponding variation ed between winter and summer is $\frac{1}{2}$ m/sec. ies are plausible, but so small as to be ctable. From the point of view of stress, d patterns are shown in figs. 2 and 3. The nal stress is too large, and the distribution The meridional-stress distribution, on the , is in phase with the monsoon winds, and ude is about what could be expected.

xamples can be summarized as follows: ut, relative to average conditions, there is a n winter over central Asia of (1) air mass d by surface pressure), (2) anticyclonic (as revealed, for example, by pressures (3) southward stress (as revealed, for y excess in pressure against the northern ne Himalayas as compared to pressure at ng levels on the southern slopes). Each of factors would be associated with a winter nt $c$ of the north pole of rotation towards lacement in spring by T$c$, or 1.2 $c$, towards These circumstances are, as a whole, in with what is observed. We may, therefore, effect of winds to augment the effect of the mass. On the basis of numerical values, we the two effects to be of the same order of

al results are summarized in table 4. The ift in air mass accounts for three fourths st term, the component in sin $\Theta$ of $\mu$. Snow ser role, but even the effect of seasonal vegetation is not wholly negligible. Under natter, Jeffreys includes the rise of sap in he formation of the annual parts in herbs duous parts in trees.

ct of winds from the angular-momentum was computed with use of seasonal charts mb surface. The totals are quite unreliable, or $\lambda$, on account of internal cancellation. n be said is that the computed values are of rder of magnitude as the observed values. of ocean currents is very much smaller.

gard to the wind-stress approach, it is to treat separately skin friction and the effect. Skin friction over the ocean is Over land, it is not sufficiently well known alculations. In general, the roughness there ut the winds weaker. The mountain effect merican continent, due largely to pressure across the Rocky Mountains and the adas, is quite small. On the other hand, if that during the monsoon winds the pressure against the Himalayas is larger on the upwind side than at corresponding levels on the downwind side, a reasonable estimate for the pressure difference can lead to one-third of the observed effect.

Theoretically, the angular-momentum approach and the torque approach should lead to nearly identical results. In practice, we find the former to be highly inaccurate, and the latter, at the present time, incomplete. The torque approach is potentially the more accurate[9], and there is reason to believe that the mountain effect against the Himalayas alone would give a fair account for the total effect of winds. This is because the wobble is twice as sensitive to meridional stresses as to zonal stresses, because the Himalayas are the largest east-west mountain chain, and subject to the strongest known variations of meridional winds. A quantitative estimate of the wind effect must be left to the future. The principal need is for station-level pressures from an adequate number of weather stations on the Indian and Chinese sides of the Himalayas. In the meantime, our conclusion will have to be limited to the statement that the effect of winds can be expected to be roughly in phase with the observed effect, and not necessarily small compared to the effects investigated by Jeffreys.

If the discrepancy between computed and observed values can be somewhat narrowed from what it is at present, the opportunity presents itself of approaching the problem from a reverse point of view: of using astronomic observations to measure certain fundamental modes[10] in the annual oscillation of the atmosphere. Such a method is inherently capable of far greater accuracy than one based on the interpolation of data from scattered weather-stations. It may also permit some estimate of changes, from year to year, over the last half century.[11] One difficulty would be the distinction between the effects of shift in air mass and of variable winds.

*Acknowledgments.*—We are greatly indebted to Prof. Yale Mintz for his help and advice.

## APPENDIX

For the geostrophic winds, we computed the tesseral harmonic coefficients of the height, $h(\theta, \phi)$, of the 500-mb surface, according to

$$\begin{bmatrix} G^1_n \\ H^1_n \end{bmatrix} = \frac{2n+1}{4\pi} \int_0^{2\pi} \int_0^{\pi} h(\theta, \phi)\, P^1_n(\theta) \times \begin{bmatrix} \cos \phi \\ \sin \phi \end{bmatrix} \sin \theta \, d\theta \, d\phi. \qquad (22)$$

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[9] The opposite is true in computing the effect of winds on the length of day (Mintz and Munk, 1951).

[10] An additional mode, not considered here, might be derived from astronomic observations concerning an annual variation in the length of the day (Mintz and Munk, 1951).

[11] Some rough computations for the period 1921–1930 have been made by R. C. Cowen (*Polar wanderings and the shifting of the atmospheric mass,* M.S. thesis at Mass. Inst. Tech., 1950, unpublished).

Values of $h$ were read off for every 20 deg long and every 5 deg lat, from 55°S to 75°N. For every latitude, values of $\sin\phi$ and $\cos\phi$ were plotted against $h$, and the resulting closed curves were planimetered to obtain

$$\int_{h(\theta,0)}^{h(\theta,2\pi)} \sin\phi\, dh = -\int_0^{2\pi} h(\theta,\phi)\cos\phi\, d\phi,$$

and similarly for $\cos\phi$. This integral (extrapolated to the poles) was multiplied by the successive $P_n^1(\theta)$ $\sin\theta$ at the 5-deg intervals of $\theta$, and summed by the trapezoid rule, to obtain (22).

## REFERENCES

Brooks, C. E. P., *et al.*, 1950: Upper winds over the world. *Geophys. Mem.*, 10, No. 85, 150 pp.

Fuglister, F. C., 1951: Annual variations in current speeds in the Gulf Stream system. *J. marine Res.*, 10, 119–127.

Iselin, C. O'D., 1940: Preliminary report on long-period variations in the transport of the Gulf Stream system. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean. Instn.*, **8**, No. 1, 40 pp.

Jeffreys, H., 1915–16: Causes contributory to the a
tion of latitude. *Roy. astr. Soc., Mon. Notices,*

Mintz, Y., 1951: The geostrophic poleward flux
momentum. *Tellus*, **3**, 195–200.

——, and W. Munk, 1951: The effect of winds and
length of the day. *Tellus*, **3**, 117–121.

Munk, W. H., 1950: On the wind-driven ocean
*J. Meteor.*, **7**, 79–93.

——, and G. F. Carrier, 1950: The wind-driven ocean
in ocean basins of various shapes. *Tellus*, **2**, 15

——, and R. L. Miller, 1950: Variation in the eart
velocity resulting from fluctuations in atmos
oceanic circulation. *Tellus*, **2**, 93–101.

——, and E. Palmén, 1951: Notes on the dynamics
arctic circumpolar current. *Tellus*, **3**, 53–55.

Rosenhead, L., 1929: The annual variation in latitude
*Soc., Mon. Notices, Geophys. Suppl.*, **2**, 140–170

Schmidt, A., 1935: *Tafeln der normierten Kugelfunkti
Formeln zur Entwicklung.* Gotha, Engelhardt-Re

Spitaler, R., 1901: Die Periodischen Luftmassenvers
und ihr Einfluss auf die Lagenänderungen de
(Breitenschwankungen). *Petermanns Mitteilu*
gänzungsband XXIX, Heft 137.

Van Den Dungen, F. H., *et al.*, 1950: On the seasonal
of the rotation of the terrestrial globe. *Bull.
Cl. Sci.*, **36**, 388–402.

603

PARKER, FRANCES L., FRED B. PHLEGER and JEAN F. PEIRSON. Ecology of foraminifera from San Antonio Bay and environs, southwest Texas. Spec. Publ. no. 2, Cushman Found., 72 pp., 1953. (Unavailable for exchange.)

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# RESURGENT POPULATIONS OF LITTORAL MARINE INVERTEBRATES AND THEIR DEPENDENCE ON OCEAN CURRENTS AND TIDAL CURRENTS[1]

A curious departure from the usual local fluctuations in the populations of marine invertebrates is the sudden appearance of a resurgent population in which the numbers may be hundreds or thousands of times larger than in the immediately preceding or following years. On sandy beaches in several parts of the world are species of bivalve mollusks belonging to the genus *Donax*. Some of these species occasionally experience an enormous increase in the numbers of individuals constituting a local population for one to three years and then re-

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[1] Contributions from the Scripps Institution of Oceanography, of the University of California. New series, No. 604.

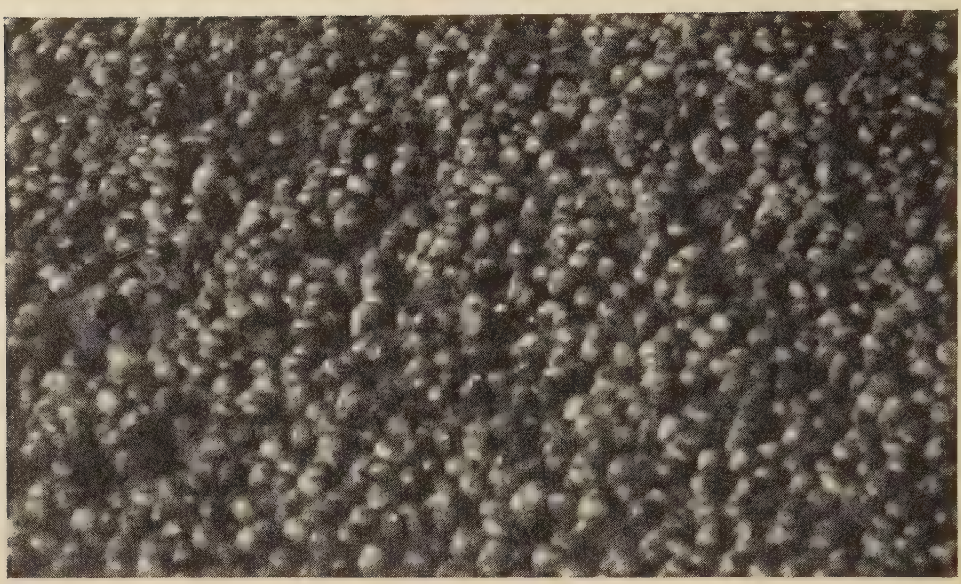

FIG 1. Small portion of resurgent population of *Donax gouldi* on the beach at La Jolla, California, in the autumn of 1950. This population, with an average density exceeding 20,000 individuals per square meter, extended with some interruptions in a band 2 to 5 meters wide for more than 5 miles along the intertidal zone. Nearly all the individuals are shown in their natural position, with only their posterior ends exposed. One-third natural size.

turn to their former numbers or disappear completely in that locality. The cause or causes which are responsible for their resurgences can seldom be found.

Such local resurgent populations of *Donax gouldi* Dall have been recorded on the coast of southern California at La Jolla in 1894–95, 1909–10, 1913–15, 1931–32, 1934, 1937–38, and have doubtless occurred in earlier years. One of the most extensive resurgences on that coast previous to 1949 was in 1937–1938. At that time the suddenly increased population extended in many locations for several hundred miles along the coast, with the little clams almost in contact and in such vast quantities that they were used extensively for broth and the broth was also canned commercially. In the late summer of 1938 the deaths in this immense population increased to epidemic proportions and by the end of October many of the beaches from Santa Monica, California, to Ensenada, Baja California, were thickly covered with the empty shells. Many of the dying clams were infested with trematode cercariae but although some kind of a minute pathogenic organism was suspected of having been responsible for the deaths, such an organism was not discovered.

The beach near the Scripps Institution of Oceanography at La Jolly was searched at frequent intervals during the ensuing half year but not a single individual could be found in an area where millions had existed a few months previously. The larvae brought in by currents from localities where the extermination had not been complete eventually repopulated the area as small, but fluctuating, populations for the next ten years, although very few individuals grew to more than half the normal adult size.

In the spring of 1949 the local population of *Donax* in the intertidal zone and below did not exceed one individual per square meter but during the summer there came another resurgence, this time of quite unusual magnitude. As the young clams increased in size they were not only in contact but crowded into several layers (Fig. 1). An average of more than 20,000 individuals per square meter formed a broad band from 2 to 5 meters wide in the intertidal zone and extended, with some interruptions, for more than 5 miles along the sandy beaches. This population presumably resulted from swarms of larvae brought by ocean currents from a beach about 11 miles distant or from some other beach within 60 miles, since these currents have an average velocity of 4 to 5 miles per day.

This dense population continued, but with considerable mortality, for almost two years, when approximately half of the individuals died after spawning in July, 1951. Those remaining still formed a dense population in many areas, but as soon as spawning began the following spring the mortality increased until about the middle of July, 1952, when only about 20 individuals per square meter, or one-tenth of one per cent of the early population, remained. Nearly all of these died within a period of a few days. The deaths included not only the members of the resurgent population, which had then attained the ripe old age of 3 years, but also nearly all the younger individuals which had reached the beach in the two intervening years, and which had managed to survive in the less crowded situations until the final catastrophe. Again, as in 1938, extended search along the beach, both in the intertidal zone and below has failed to reveal a dozen individuals, old or young, with the exception of one small area in which all the members of the resurgent population died, while the younger year-classes survived. Coincident with the final period of mortality was the arrival of a dense population of dinoflagellates but it is uncertain whether these organisms had any influence on the death rate of the clams.

No completely satisfactory explanation for this occurrence has been found. Samples of the population had been examined microscopically once each month or oftener throughout its 3-year history.[2] Infestation with trematode parasites was found in about 10 per cent of the clams and many unicellular organisms thought to be commensal were usually present and the expected minute pathogenic organisms could be detected. The trematodes may render the individual sterile but do not ordinarily kill it. Pelseneer (1928), however, attributed the death of a large population of *Donax vittatus* on the coast of France to heavy infestation with similar cercariae but it seems possible that other minute pathogenic organisms may have been involved.

The life span of *Donax* in this locality is seldom more than 3 years and that may account for the deaths of some of the older individuals but not those of the younger year-classes. The circumstances point strongly to an epidemic disease comparable with one of those that have caused so much mortality among the oysters along the Atlantic and Gulf coasts, as well as in Europe and other parts of the world.

As is usual in this and other species of sand-dwelling clams, the moribund individuals lay fully exposed on the surface of the sand for several days before death, apparently too feeble to bury themselves after having been washed out by the surf. The bodies were thin and watery, often with greenish exudations of blood and blood corpuscles, together with many minute objects thought to be responsible for the epidemic although their precise nature could not be determined.

The reproductive capacity of this species, as of most other pelecypods, is very great, since each mature female may produce 50,000 to 100,000 ova during the spawning season. The fertilized ova develop into pelagic larvae which may be carried for several miles during the larval period by the ocean currents which in this locality, as already mentioned, have an average velocity of 4 to 5 miles per day. Most of the larvae presumably perish because of unfavorable temperature, predation by enemies or adverse currents which carry them too far from shore but others may reach a suitable sandy beach at the precise time when they are ready for transformation to the adult condition.

The inshore currents may flow either north or south and the direction is frequently reversed. For this reason the swarms of larvae may be carried for several miles from their place of origin and when they are ready for settling they may be returned to the beach from which they started. In such a case a continuously maximum population might be maintained. The infrequency of resurgent populations indicates that this seldom happens on this part of the coast, since each beach usually supplies the population for some other beaches.

During the years between the periods of resurgence the species is maintained locally as a small but fluctuating population or it may disappear almost completely. The increase in the population is limited by heavy surf which may carry the clams to far out to sea or bury them too deeply in the shifting sand, as well as by such predators as elasmobranchs, bony fishes and gulls or by trematodes and other parasites. Several species of fishes nip off the siphons but these can be regenerated.

The range of the species is reported to extend from north of Point Conception, California, to the Gulf of California and southward to Acapulco, Mexico, a distance of more than 2,000 miles. At various places along this extent of coastline, it is probable that there are several local resurgences each year, for this is a species that may be very abundant in one locality while it is scarce in another. The differences are presumably caused in large measure by vagaries in the ocean currents which transport the larvae.

There are many examples of similar resurgent populations of marine invertebrates but usually on a less extensive scale. Coe (1946) reported the sudden appearance of a population of the bay mussel (*Mytilus edulis diegensis* Coe) on the coast of southern California. In 1943 a small colony of this subspecies was found on the pier at La Jolla where none had been seen in the immediately preceding years. The following summer the mussels had multiplied so rapidly that they covered all the available spaces in the intertidal zone on the pier as well as on most of the adjacent rocks. In many situations there were a hundred times as many young as could have grown to maturity because of lack of space. Vast colonies were started in places unsuitable for survival.

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[2] The writer is indebted to Mr. James Kittridge of this Institution for assistance in making some of the collections.

They were soon distributed widely along the coast and in some localities became a nuisance by attaching themselves to boats and piers, as well as by clogging the intake pipes of salt-water cooling systems. Following that resurgence the numbers decreased to relatively small local populations. The larvae may be carried for many miles by the ocean currents during their pelagic existence.

The wide fluctuations in the populations of the Pismo clam (*Tivela stultorum* Mawe) at Pismo Beach, California, from 1927 to 1949, are tabulated by Coe and Fitch (1950) from the annual census made by the California Bureau of Marine Fisheries. The relative size of the population each year was estimated by collecting all the clams on a definite area of the beach. Although there were millions of clams on this and adjacent beaches and each large female can be expected to produce more than 10,000,000 eggs each year, the number of young which became established on the beach was relatively extremely small. This number has been highly variable, however, presumably because of the fluctuations in the environmental conditions, including the vagaries of the ocean currents which must be depended upon to bring the larvae to the beach at the end of their pelagic stage.

In the measured area there were only 6 yearling clams in 1928, as compared with 468 the following year. None were found in 1934 but there were 758 in 1935; 743 in 1937 and only 9 in 1938, and 1 in 1949; in 1950 and 1951 there were none. No evidence has been found of any change in the spawning activities of the clams, nor has there been any considerable variation in the environmental conditions. It is therefore concluded that adverse ocean currents have carried the vast swarms of larvae too far out to sea or to some other areas along the coast, many of which are not suitable for the survival of this species. The small numbers in recent years are not considered as evidence that more favorable conditions with a resurgent population may not appear in the immediate future as the result of random fluctuations in the environment, including the direction of the ocean currents.

The great variability in the number of yearlings in the measured area in successive years is shown by the following list, beginning with 1927: 37, 6, 468, 357, 871, 44, 199, 0, 758, 142, 743, 9, 23, 24, 13, no record for 1942 to 1945, 384, 31, –, 1, 0, 0. For the first 12 years there is indication of a biennial periodicity, each alternate year, beginning with the first, having a larger population of young than each intervening year. No satisfactory explanation for these observed fluctuations has been found. The environmental conditions are not known to have shown corresponding variations, but it may be suggested that one of the reasons may have been that adverse ocean currents in the years with the smaller populations carried most of the larvae away from the beach when they were ready for settling. Otherwise the series shows no evidence of a cyclical periodicity.

Records of the set of young oysters in Long Island sound for the past 70 years, compiled by Loosanoff and Engel (1940) likewise show very wide fluctuations in numbers. Heavy sets were reported in 12 of the 18 years prior to 1900 but there have been only 6 years since that date when the sets were considered heavy. From 1906 to 1924 there were only light sets and failures, with medium sets in 1926, 1934, 1937, 1941, and 1945. Heavy sets occurred in 1904, 1925, 1928, 1930, 1939, and 1940. These records likewise show no evidence of a cyclical periodicity.

Not only the larvae of the species mentioned, but also those of other littoral invertebrates such as most bivalve and some univalve mollusks, worms, crustaceans, echinoderms, tunicates and others which have a prolonged pelagic existence may be carried several to many miles from their place of origin. Their survival depends not alone on the vicissitudes encountered on their journey but also on the chance of arriving at some suitable locality at the time when they are ready for metamorphosis and settling on or in the substratum.

They may then repopulate a depleted area or complete with the resident population for food and space for attachment or shelter. Furthermore they may maintain a population in localities where reproduction does not usually take place. The chances of reaching a place suitable for existence as adults are obviously greater in bays and partially enclosed bodies of water than on the open seacoast where so many of them are likely to perish by being carried too far out to sea.

During certain tidal periods in bays, sounds and estuaries the larvae may be carried back and forth at rates of several miles an hour. Many of them are drifted too far out to sea or to other areas which are unsuitable for survival. Likewise larvae from the open coast may be brought into estuaries where the salinity is too low or where other conditions are unfavorable.

By means of these currents the geographical range of a species with pelagic larvae may be extended in favorable seasons far beyond the usual limits but only to have the range restricted again when more rigorous conditions return. The population will thereby fluctuate irregularly in distribution and in numbers, with an occasional resurgence in varying degrees of magnitude.

It is concluded that resurgent populations of marine littoral invertebrates in any locality depend upon a combination of the following circumstances: (a) a large spawning population at that locality or at some other place not too many miles distant; (b) suitable conditions during the period of pelagic larval life; (c) favorable currents which may bring the swarms of larvae to that locality at the exact time when they are ready for metamorphosis to the adult form and settling in or on the substratum; and (d) adequate opportunities for continued growth.

As a consequence of these currents, local conservation measures usually have little influence on the subsequent populations of that immediate neighborhood, although they may benefit some other locality to which the larvae may be carried. In order to be effective in any one locality it is therefore necessary that the conservation should include a sufficiently large extent of coast line to insure that each locality may supply larvae to the others. Only occasionally will a large proportion of the larvae be returned to their place of origin.

## SUMMARY

Resurgent populations of the bean clam, *Donax gouldi,* have occurred on the beach at La Jolla, California, seven times during the past 58 years. On most of these occasions the local population was a thousand to ten thousand fold larger than in the immediately preceding or the following years. These populations doubtless resulted from the arrival of swarms of pelagic larvae which originated elsewhere and were brough to the local beach by ocean currents at the time when they were ready for transformation and settling in the sand.

Such populations of *Donax* are always short lived. In one of them, numbering 20,000 individuals per square meter one year after arrival and extending in a band 2 to 5 meters wide for 5 miles, disease was prevalent, mortality rate was high and, with very few exceptions, all the members of this immense population were dead within 3 years.

Less extensive resurgent populations are reported for the Pismo clam, the bay-mussel and oysters. The local abundance or scarcity of other species of marine littoral invertebrates with pelagic larvae, including those of economic importance, likewise depends to a large extent on the vagaries of the ocean currents or tidal currents which may bring the larvae to that locality at the time when they are ready for transformation to the adult condition and settling on the substratum.

## REFERENCES

**Coe, W. R.** 1946. A resurgent population of the California bay-mussel (*Mytilus edulis diegensis*). Jour. Morph., **78**: 85–104.

**Coe, W. R., and J. E. Fitch.** 1950. Population studies, local growth rates and reproduction of the Pismo clam (*Tivela stultorum*). Jour. Marine Res., **9**: 188–210.

**Loosanoff, V. L., and J. B. Engel.** 1940. Spawning and setting of oysters in Long Island Sound in 1937 and discussion of the method for predicting the intensity and time of oyster setting. U. S. Bur. Fish., Bull., **49**: 217–255.

**Pelseneer, P.** 1928. Les parasites des mollusques et les mollusques parasites. Bull. Soc. Zool. France, **53**: 158–189.

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# PRODUCTION OF NITRITE FROM AMMONIA BY METHANE OXIDIZING BACTERIA[1]

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ethane oxidizing bacteria appear to be widely ibuted in soil and also in marine mud. Hut- and ZoBell (1949) found methane oxidizers ; per cent of 299 one-gram samples of surface and marine mud, where they are believed to an important part in the conservation of on by converting methane into carbon di- e and organic matter in the form of bacterial substance. Such bacteria also may play a in the transformation of nitrogen com- ds. This paper is concerned primarily with enting evidence that ammonia is oxidized trite by certain methane oxidizing bacteria.

## MEDIA AND METHODS

e organisms were cultivated in a medium isting of 0.1 per cent $NH_4Cl$, 0.05 per cent $PO_4$, 0.01 per cent $CaCO_3$, and 0.01 per cent $O_4 \cdot 7H_2O$ in distilled water. In some experi- ts other substances were tried as the nitrogen ce. The medium was dispensed in two stop- d 180 ml bottles connected with a siphon. bottle was provided with a stopcock to it the introduction of approximately 160 f the gas mixture over 20 ml of the liquid ium. The other bottle, the reservoir, was l with medium exposed to the outside atmos- e through a cotton plug. Thus, as gas was umed by the bacteria in the culture bottle, d medium was siphoned over from the reser- bottle. Both bottles were calibrated with uated scales to provide for reading to the est 0.5 ml volumes, which were corrected ressure and temperature. Aseptic precau- were exercised in all manipulations.

e culture bottle was fitted with a tube and d with a vaccine cap to permit the removal of liquid samples with a hypodermic syringe for chemical analyses without interrupting the experiment. Nitrite was detected by the method of Griess or determined quantitatively in the Klett-Summerson photoelectric colorimeter (Rakestraw, 1936). Brucine reagent was used to test for nitrate after nitrite had been removed by boiling the acidified samples with urea solution. Ammonia was estimated by Nessler's reagent. Gas analyses were made by the method of Matuszak (1934). Some gas samples were examined by mass spectrometer through the courtesy of cooperating laboratories.

By plating procedures pure cultures were isolated from enrichment cultures prepared by five or six serial transfers to the mineral salts medium with methane serving as the sole source of energy. Discrete colonies were picked from the mineral salts medium solidified with 2 per cent washed agar. The agar plates were incubated in jars filled with a gas mixture consisting of 10 per cent carbon dioxide, 40 per cent methane, and 50 per cent oxygen.

## DESCRIPTION OF THE BACTERIA

The colonies of the bacteria were 0.1 to 5 mm in diameter; all were circular, convex, colorless, and pearly in appearance. The cells were gram negative, nonsporeforming rods ranging in size from 0.6 to 1.0 by 2.0 to 3.4 $\mu$ and usually lacked flagella although the cells of some cultures possessed a single polar flagellum. They were able to develop in media when supplied with a mixture of methane, oxygen, and carbon dioxide. In contrast to the membranous growth characteristic of *Methanomonas methanica* (Breed *et al.*, 1948), most of our cultures of methane oxidizers produced a fairly heavy turbidity in liquid mineral media with no membrane formation.

Unlike the methane oxidizers studied by Münz (1915), which were claimed to grow heterotrophically, none of our pure cultures

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isolated from a medium in which methane had served as the sole source of energy was able to develop in similar medium enriched with peptone in the absence of methane. Likewise neither acetate, lactate, glutamate, glycerol, glucose, lactose, sucrose, starch, nor asparagine served as a sole source of energy for our methane oxidizers. None of these substances in concentrations of 0.1 per cent in mineral media inhibited methane consumption by our cultures, contrary to the report of Aiyer (1920) that after contact with organic matter such organisms lose all power of oxidizing methane. In fact, some of these substances seemed to stimulate the activity of pure cultures, but in crude cultures contaminating heterotrophs generally overgrew the methane oxidizers. The stimulating effect of 5 $\mu$g per L of thiamin, pyridoxine, riboflavin, and nicotinamide was especially notable when starting with small inocula of pure cultures.

Part of the cultures oxidized ethane, ethylene, and propane as readily as methane. A few oxidized butane more readily than any other gaseous hydrocarbons, but others failed to attack any hydrocarbon tested except methane. Whether these are constitutive differences in varieties or species or superficial differences attributable to adaptive enzymes or environmental conditions remains to be determined. Slavnina (1948) described a methane oxidizer that utilized both ethane and propane, and the one described by Tausz and Donath (1930) allegedly assimilated all saturated aliphatic hydrocarbons from methane to decane. Neither ethane nor ethylene was utilized by the methane oxidizer of Münz (1915). Virtually all kinds of hydrocarbons are susceptible to microbial attack (ZoBell, 1946, 1950), but only a specialized few microorganisms attack methane.

### EVIDENCE OF AMMONIA OXIDATION

In experiments originally designed to determine the nitrogen requirements of methane oxidizers, nitrite was detected in certain pure cultures developing in mineral medium enriched with $NH_4Cl$. Illustrative data are summarized in table 1, which shows the amounts of methane consumed in media treated with various compounds to give 10 mg atoms of nitrogen per liter. The relative abundance of ammonia, nitrite, and nitrate at the end of the experiment also is shown.

Further tests with three different pure cultu confirmed that these methane oxidizers utili almost equally well either ammonia, nitra glutamic acid, or peptone as a source of nitrog None developed in media containing nitrite glycine as the sole source of nitrogen. By sup menting the atmosphere of $CO_2$, $CH_4$, and with various proportions of $N_2$ it was establis that the methane oxidizers required fixed nit gen.

Several, but not all, pure cultures tested w found to produce appreciable quantities of nit in media enriched with ammonium salts. Nit was detected only in those cultures that w developing in ammoniacal medium or in me to which nitrite had been added intentiona Thus, the possibilities were ruled out that nit was introduced with the inocula or that it some other extraneous origin. Although nitr was utilized by the methane oxidizers almos readily as ammonia, no nitrite could be detec in nitrate cultures.

More difficult to rule out was the possible volvement of *Nitrobacterieae* which are o found associated with methane oxidizers nature. Cultures of methane oxidizers that dized methane to nitrite were subjected rigorous purification procedures in an atte to eliminate contaminants of any kind. Disc colonies that developed on mineral salts enriched with nitrate as the sole source of ni gen in an atmosphere of 10 per cent $CO_2$, per cent $CH_4$, and 50 per cent $O_2$ were pic and transferred from plate to plate five succes times. Each set of plates was examined for taminants, and representative colonies of m ane oxidizers were picked for microsc examination. Only methane oxidizers ha similar morphological and colonial characteri appeared on the agar plates.

When inoculated into Winogradsky's med for the cultivation of *Nitrosomonas* (Bol 1935), none of the purified cultures exhibited activity during six weeks' incubation at 30 an atmosphere of either air or a mixture o per cent air with 10 per cent $CO_2$. Howeve an atmosphere of methane, oxygen, and the cultures became turbid, consumed gas, produced nitrite (table 2).

Further tests on the ability of methane dizing bacteria to oxidize ammonia were b upon the time interval required for both o

. Nitrite was determined quantitatively at beginning of the experiment and after ent periods of incubation at 32 C. The cul- and sterile controls were maintained in an sphere of 30 per cent $CH_4$, 60 per cent $O_2$, 10 per cent $CO_2$. Figure 1 shows the amounts ethane consumed and nitrite produced after rent periods of time. How nearly the rate itrite production parallels the rate of meth- oxidation is shown by the straight line n through the points in the scatter diagram ure 2, in which nitrite production is plotted nst methane oxidation for three cultures. l available evidence indicates that the same organisms are responsible for methane oxidation and for the oxidation of ammonia to nitrite.

TABLE 1

*ane consumed by culture 37:146-2 during 31 ' incubation at 30 C in mineral salts medium ed with various nitrogen compounds to give 10 toms N per liter in an atmosphere initially sting of 10 per cent $CO_2$, 40 per cent $CH_4$, and 50 per cent $O_2$*

| NITROGEN COMPOUND | METHANE CONSUMED | TERMINAL PRESENCE OF | | |
|---|---|---|---|---|
| | | $NH_4^+$ | $NO_2^-$ | $NO_3^-$ |
| | *ml* | | | |
| e (control).. | 0.0 | – | – | – |
| Cl......... | 38.6 | ++++ | ++ | – |
| $)_2$......... | 0.0 | – | ++++ | – |
| $)_3$......... | 31.9 | – | – | ++++ |
| amic acid.. | 38.0 | + | – | – |
| ine........ | 0.0 | – | – | – |
| o peptone.. | 38.9 | + | – | – |

TABLE 2

*ence of activity of rigorously purified cultures nethane oxidizing bacteria in ammoniacal mineral salts medium*

| TURE MBER | GASEOUS ATMOSPHERE | RELATIVE TURBIDITY | GAS CONSUMED | NITRITE TEST |
|---|---|---|---|---|
| | | | *ml* | |
| 46-1 | Ordinary air | – | 0 | – |
| 46-1 | $CH_4$, $O_2$, $CO_2$ | +++ | 37 | ++ |
| 46-2 | Ordinary air | – | 0 | – |
| 46-2 | $CH_4$, $O_2$, $CO_2$ | ++++ | 49 | +++ |
| 46-3 | Ordinary air | – | 0 | – |
| 46-3 | $CH_4$, $O_2$, $CO_2$ | +++ | 45 | ++ |
| 50-1 | Ordinary air | – | 0 | – |
| 50-1 | $CH_4$, $O_2$, $CO_2$ | +++ | 32 | ++ |

Out of a total of 67 enrichment cultures of methane oxidizing bacteria isolated from marine mud and soil samples, 21 were found to oxidize ammonia to nitrite in the presence of methane. None of them produced nitrite in the absence of methane. On the other hand, none of the 34 enrichment cultures of ammonia oxidizing bacteria recovered from marine mud and soil samples by the methods of Boltjes (1935) was able to oxidize methane.

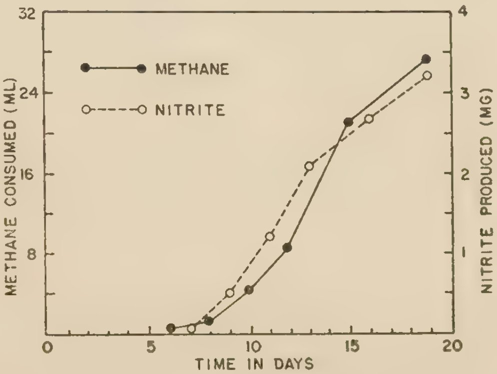

*Figure 1.* Cumulative total amounts of methane consumed and of nitrite produced by culture 37:146-2 incubated 19 days at 32 C.

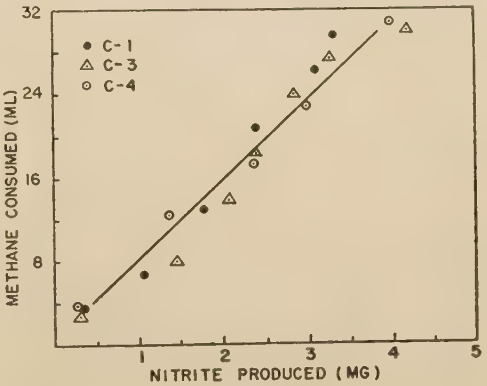

*Figure 2.* Relation of methane consumption to nitrite production by cultures 37:146-1, 37:146-3, and 37:146-4 incubated 19 days at 32 C.

ACKNOWLEDGMENTS

The authors are indebted to Rose Marie Cassady and Richard Y. Morita for technical assistance in some of these experiments. The

cooperation of members of the Advisory Committee on Fundamental Research of the American Petroleum Institute also is acknowledged with thanks.

## SUMMARY

Methane oxidizing bacteria are able to utilize almost equally well either $NH_4Cl$, $KNO_3$, peptone, or glutamic acid as nitrogen sources. Neither $KNO_2$ nor glycine was utilized. Growing cultures of the bacteria require fixed nitrogen to oxidize methane.

Data are presented which indicate that certain methane oxidizing bacteria are able to oxidize ammonia to nitrite. They do not produce nitrite from nitrate.

## REFERENCES

AIYER, P. A. S. 1920 The gases of swamp rice soils. Part V. A methane-oxidizing bacterium from rice soils. Mem. Dept. Agr. India, Chem. Ser., **5**, 173–180.

BOLTJES, T. Y. K. 1935 Untersuchungen über die nitrifizierenden Bakterien. Arch. Mikrobiol., **6**, 79–138.

BREED, R. S., MURRAY, E. G. D., AND HITCHENS, A. P. 1948 *Bergey's manual of determinati* *bacteriology*. 6th ed. Williams & Wilkin Co., Baltimore, Md.

HUTTON, W. E., AND ZOBELL, C. E. 1949 Th occurrence and characteristics of methan oxidizing bacteria in marine sediments. J Bact., **58**, 463–473.

MATUSZAK, M. P. 1934 Unitized gas analysi apparatus. Ind. Eng. Chem., Anal. Ed., 6 72–78.

MÜNZ, E. 1915 Zur Physiologie der Methan bakterien. Dissertation, Friedrichs-Univer sität, Halle, Germany, 61 pp.

RAKESTRAW, N. W. 1936 The occurrence an significance of nitrite in the sea. Biol. Bull. **71**, 133–167.

SLAVNINA, G. P. 1948 Fluorescence method applied to the study of some hydrocarbon oxidizing bacteria. Mikrobiologiya, **17**, 76–81.

TAUSZ, J., AND DONATH, P. 1930 Über die Oxydation des Wasserstoffs und der Kohlenwasserstoffe mittels Bakterien. Z. physiol. Chem., **190**, 141–168.

ZOBELL, C. E. 1946 Action of microorganisms on hydrocarbons. Bact. Revs., **10**, 1–49.

ZOBELL, C. E. 1950 Assimilation of hydrocarbons by microorganisms. Advances in Enzymol., **10**, 443–486.

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# per Partition Chromatography
# Taxonomic Studies[1]

driano A. Buzzati-Traverso[2] and
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*iversity of California, La Jolla*

Paper partition chromatography, as applied to
esh tissues of several species of fish, yields re-
lts that seem to have value for taxonomic studies.
ne following technique is being used: (1) Approxi-
ately 8 mm$^3$ of various tissues, such as muscle, liver,
d eye lens of fresh fishes, are placed on Whatman
1 filter paper and squashed with the aid of a glass
stle with a flattened tip, to form a spot about ½ in.
diameter. (Muscle proves to be the most favorable
aterial.) (2) The tissue is allowed to dry at room
mperature. (3) The chromatogram is developed in
e direction by descending flow of the solvent. Two
lvent mixtures are used. One is comprised of 2 parts
*n*-propanol, and 1 part of 1% ammonia; the other
a mixture of 4 parts of *n*-butanol and 1 part of
acial acetic acid, made up with 5 parts of water.
) After development, the chromatograms are first
udied under ultraviolet lamps for the presence of
orescent spots. (5) The chromatograms are then
rayed with a 0.2% solution of ninhydrin in 95°
hanol, to which 5% 2,4,6-collidine is added before
e. Black-and-white or colored photographs of the
orescent and of the ninhydrin-positive pattern are
ade and kept for permanent record.

Fluorescent and ninhydrin-positive patterns of a
rtain tissue taken from various specimens of the
me species are remarkably constant, irrespective of
e size or age of the fish. On the other hand, patterns
tained from muscle of different species show con-
ant and easily recognizable differences (Fig. 1). In
neral, in the preliminary tests, the closer the taxo-
mic position of any two or more species studied, the
eater the similarity of their chromatographic pat-
ns. No extensive attempts have been made to iden-
y the chemical nature of the substances involved,
t it can be said that free amino acids do not play an
portant role. Comparable results have been obtained
other animal phyla. Preliminary results indicate
t the same technique can be used to distinguish

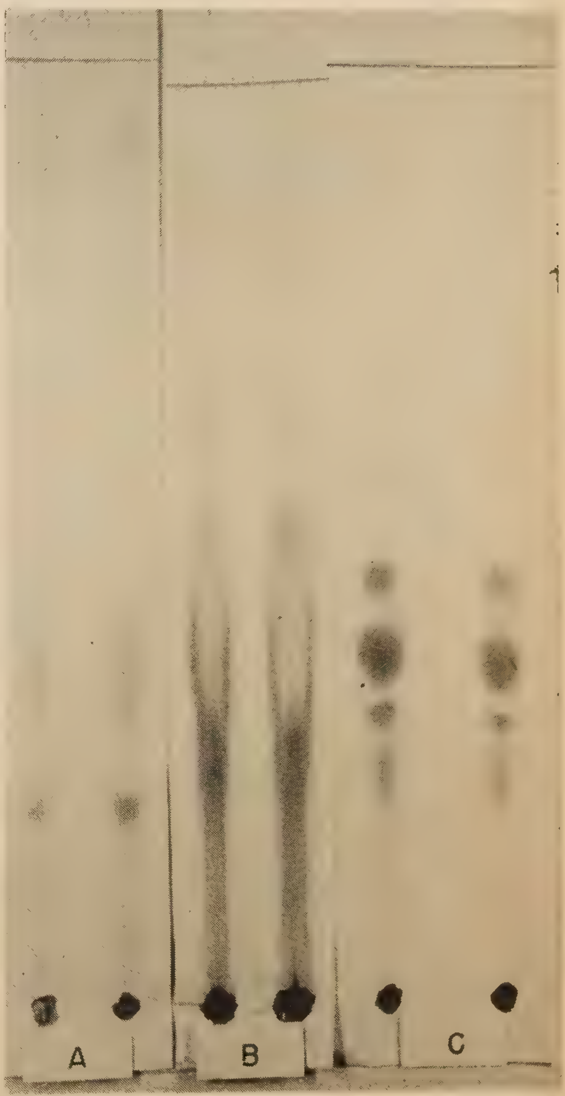

FIG. 1. Ninhydrin-positive patterns of *A*, *Paralabrax clathratus*; *B*, *P. maculatofasciatus*; and *C*, *Hysterocarpus traski*. Two samples of each species are presented.

stocks of the same species belonging to populations geographically separated.

On the basis of the results obtained, it appears that this technique will become a useful tool in taxonomic and population-genetical studies, and that it may perhaps also be used for an understanding of phylogenetic relationships in biochemical terms. More complete accounts will be published elsewhere.

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# Ichthyological Notes

## CCURRENCE OF AN OIL GLOBULE IN S OF PLEURONECTID FLATFISHES.[1]—

ie literature on eggs of flatfishes it is commonly d that an oil globule is present in the family idae and absent in the family Pleuronectidae. character was included by Norman (1934, ograph of Flatfishes, vol. 1) both in the diags and in the general discussion of these two lies, and has been cited and used variously by equent authors, including Orcutt (1950, Calif. Fish and Game, Fish Bull. No. 78).

veral apparent exceptions to this pleuronectid characterization have long been carried in the ature. From work by Anderton (1907, Trans. :. New Zealand Inst., 39: 477–95) and Thomson Anderton (1921, Bull. New Zealand Bd. Sci. 2: 9–131) it was known that from one to several lobules occur in the eggs of six flatfishes of the *mbosolea* group, which was treated by Norman subfamily of the Pleuronectidae. Chabanaud 6, Bull. Mus. Nat. Hist. Paris, (2) 18: 160) has ntly elevated the group to family rank. In addi- to adult characters, he emphasized the presence il globules in eggs of rhombosoleids and their nce in eggs of pleuronectids, *sensu restricto* 9, Bull. Mus. Nat. Hist. Paris, (2) 21: 673–75). typical pleuronectid, *Pseudopleuronectes ameri-* *s* (Walbaum), it was reported by Breder (1922, U. S. Bur. Fish., 38: 311–15) that freshly vned eggs lack an oil globule but that many of embryos develop a transitory structure resemg it. This was interpreted as the definite occure of an oil globule in this species by Bigelow and sh (1925, Fishes of Gulf of Maine, p. 505) and Norman (*op. cit.*, p. 30). From Breder's original ription and figures, however, it can be seen rly that the structure in question is actually Kupffer's vesicle, a transitory organ of normal rrence in teleost embryos. The egg of *Pseudo-* *ronectes americanus* thus agrees with other deed pleuronectid eggs in lacking an oil globule.

he character of absence of an oil globule in ronectid eggs is so well entrenched in the litera- that it is of interest to report that certainly and probably two, exceptions to it have been id among the pleuronectid flatfishes of Calia. On two occasions the junior author has obed eggs of *Hypsopsetta guttulata* (Girard) by oping ripe adults collected off Scripps Institu-, and eggs with the same structure and developthe same easily-recognized embryonic and proal characters have occurred repeatedly in plankton samples taken off Scripps Institution during the summer of 1952. All of the eggs of this flatfish that

*Page 115*

we have seen contain a conspicuous, typical, moderately large oil globule. The egg capsule is simple, without polygonal sculpturing or other apparent texture.

The same plankton samples have occasionally included another type of flatfish egg, with an oil globule, that is possibly a pleuronectid but is not yet certainly identified. The capsule of this type of egg has the conspicuous polygonal sculpturing described by Budd (1940, Calif. Div. Fish and Game, Fish Bull. No. 56) in three of the four California species of the pleuronectid genus *Pleuronichthys*. In size, general appearance, and developmental characteristics this egg and its resulting prolarva closely resemble Budd's description and figures of *Pleuronichthys verticalis* (Jordan and Gilbert), but differ consistently in possessing a small oil globule, in color (light pigment cells brownish-orange instead of yellow), and in pattern and mode of its formation, especially on the median finfolds. Eggs and prolarvae essentially agreeing with Budd's *P. verticalis* have also been taken at La Jolla. The form with the oil globule may be *Pleuronichthys ritteri* (Starks and Morris), the only local member of the genus with eggs still undescribed, but there is also a possibility that it may represent some other pleuronectid genus. Among flatfishes, eggs with polygonal sculpturing on the capsule have apparently been reported only in *Pleuronichthys*, but this type of egg modification is also known to occur in such widely divergent families as the Macrouridae and the Callionymidae.

*Hypsopsetta* and *Pleuronichthys* are regarded as closely related and relatively primitive pleuronectid genera. It is possible that an oil globule was primitively present in pleuronectid eggs and has been lost subsequently in most of the extant evolutionary lines in the family. The Pleuronectidae and Bothidae are thought to be closely related and of common origin (Hubbs, 1945, Misc. Publ. Mus. Zool. Univ. Mich.. No. 63). The occurrence of oil globules is of such random nature in teleosts in general that its taxonomic value is usually limited to the lower categories. On present knowledge, the oil globule itself cannot be said to be either primitive or advanced.—GRACE L. ORTON AND CONRAD LIMBAUGH, *Scripps Institution of Oceanography, University of California, La Jolla, California.*

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# The Theory of Noise in Continuous Media

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It is shown that the mathematical solution of problems involving the propagation of noise is materially aided by the introduction of the space correlation function $\psi(\mathbf{x}_1, \mathbf{x}_2, \tau)$, defined as the average, over $t$, of $p(\mathbf{x}_1t)p(\mathbf{x}_2t-\tau)$, $p$ being the acoustic pressure in the noise field. The differential equations satisfied by $\psi$ are derived. Its relation to $\Psi(\alpha, \beta, \gamma)$ is discussed, $\alpha$, $\beta$, $\gamma$ being the propagation vector of a sinusoidal wave, and $\Psi/2\rho c^2$ being the density of potential energy in the $\alpha$, $\beta$, $\gamma$ space.

The theory of uniform noise fields, both isotropic and anisotropic, is developed in detail. The anisotropy caused by a reflecting plane is discussed. The radiation of noise by a vibrating plane is discussed, neglecting the reaction of the radiation on the motion of the surface. In particular, it is shown that to this approximation the sea surface cannot radiate subsonic energy into the high atmosphere because the velocity of the surface gravity waves is less than the velocity of sound in air.

The theory of noise, as here developed, is analogous to the theory of turbulence, and the relation between noise and turbulence is briefly discussed.

## ERAL DEFINITIONS AND EQUATIONS

ıalytic theory of noise fields is in many ways
ogous to the theory of electrical noise in
ıd the technique of autocorrelation is very
s assumed that the sound pressure in a noise
es the ordinary wave equation

$$c^2\nabla^2 p-\partial^2 p/\partial t^2=0. \tag{1}$$

ut those solutions of this equation that repre-
one first defines a wider class, that of average-
ons, which is narrow enough, however, to
utions that represent trains and beams of
es.
e correlation function[1] of the pressure at two points $\mathbf{x}_1$ and $\mathbf{x}_2$ is

$$\psi(\mathbf{x}_1\mathbf{x}_2\tau)=\langle p(\mathbf{x}_1t)p(\mathbf{x}_2t-\tau)\rangle, \tag{2}$$

where $\tau$ is the delay time and the angular bracket indicates the time-average

$$\langle\cdots\rangle=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}\cdots dt.$$

The solution $p$, of Eq. (1) will be called "averageable" if (a) $\psi$ exists and is everywhere finite, (b) $\psi$ does not vanish identically, and (c) the first and second derivatives of $\psi$ may be averaged by differentiating $\psi$.

An example of the consequences of the third condition is

$$\langle[\partial p(\mathbf{x}_1t)/\partial x_1][\partial p(\mathbf{x}_2t-\tau)/\partial y_2)]\rangle=\partial^2\psi/\partial x_1\partial y_2.$$

A simple example of an averageable solution that is not a noise is given by

$$p=\sin(\alpha x-\omega t),$$

for which

$$\psi=\tfrac{1}{2}\cos[\alpha(x_1-x_2)-\omega\tau].$$

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[*] ıtical leave from the Scripps Institution of Ocean-
ıe University of California. This is S. I. O. Contri-
08 (New Series).

[1] tical importance of such space correlation functions
ıas been stressed by F. V. Hunt, Proc. Inst. Radio
(1951). It has long been customary to use such space
n the theory of turbulence.

Another example is

$$p=\sin(\alpha x+\beta y-\omega t)+\sin(\alpha x-\beta y-\omega t),$$

for which

$$\psi=2\cos[\alpha(x_1-x_2)-\omega\tau]\cos\beta y_1\cos\beta y_2.$$

Most solutions of the form

$$p=\int P(\mathbf{x}\omega)\exp(-i\omega t)d\omega$$

are not averageable; with rare exceptions, the function $P$ must be such that

$$I=\int|P|^2d\omega$$

exists. But then it can be shown that

$$I=\int p^2dt,$$

and hence that $\psi(\mathbf{xx}0)$ vanishes identically. Now, it readily follows from Eq. (2) that

$$[\psi(\mathbf{x}_1\mathbf{x}_2\tau)]^2\leqslant\psi(\mathbf{x}_1\mathbf{x}_1 0)\psi(\mathbf{x}_2\mathbf{x}_2 0). \qquad (3)$$

Hence, $\psi(\mathbf{x}_1\mathbf{x}_2,\tau)$ vanishes identically—which is contrary to the definition.

It is difficult to give analytic expressions for averageable solutions other than those which are sums (or infinite series) of simple harmonic solutions. It is not reasonable to suppose that a noise in the true sense of the word, can be represented by such solutions. However, it is possible to derive equations for the space correlation functions, and these equations have solutions that do not correspond to any of the examples mentioned. It is doubtless justified to assume that these space correlation functions correspond to more general solutions of the wave equation, and do represent, among other things, noise fields. This theory of the function $\psi$ will now be developed. From Eq. (2), by replacing $t$ by $t-\tau$, one obtains the relation

$$\psi(\mathbf{x}_2,\mathbf{x}_1,-\tau)=\psi(\mathbf{x}_1,\mathbf{x}_2,\tau). \qquad (4)$$

From Eq. (1), it follows that

$$c^2\nabla_1^2\psi-\partial^2\psi/\partial\tau^2=0,\quad c^2\nabla_2^2\psi-\partial^2\psi/\partial\tau^2=0, \qquad (5)$$

$\nabla_1$ and $\nabla_2$ being the vector derivatives with respect to $\mathbf{x}_1$ and $\mathbf{x}_2$, respectively. It will be seen that the Eqs. (3), (4), and (5), together with appropriate boundary conditions, suffice to determine $\psi$.

The autocorrelation function is related to the mean potential energy of the medium by the equation

$$\langle p^2\rangle/2\rho c^2=\psi(\mathbf{x}_1\mathbf{x}_1 0)/2\rho c^2. \qquad (6)$$

Introducing the velocity components $u$, $v$, $w$ by the equations

$$\rho\partial u/\partial t=-\partial p/\partial x,\quad \text{etc.},$$

and defining

$$\psi_u=\langle u(\mathbf{x}_1 t)p(\mathbf{x}_2 t-\tau)\rangle,\quad \text{etc.},$$

$$\psi_{uv}=\langle u(\mathbf{x}_1 t)v(\mathbf{x}_2 t-\tau)\rangle,\quad \text{etc.},$$

it is seen that

$$-\rho(\partial\psi_u/\partial\tau)=\partial\psi/\partial x_1,\quad \text{etc.},$$

$$-\rho^2(\partial\psi_{uv}/\partial\tau)=\partial^2\psi/\partial x_1\partial y_2,\quad \text{etc.},$$

which enable the calculation of these other space tions. The mean energy flow has the $x$ compone

$$\langle up\rangle=\psi_u(\mathbf{xx}0),$$

and the mean density of kinetic energy is

$$\tfrac{1}{2}\rho\langle(u^2+v^2+w^2)\rangle=\tfrac{1}{2}\rho(\psi_{uu}+\psi_{vv}+\psi_{ww})_0,$$

the right side being evaluated for $\mathbf{x}_1=\mathbf{x}_2$, $\tau=0$.

Consequently, a knowledge of the function $\psi$ dependence on all seven variables, will enable calculate all of the characteristics of the nois that are usually of interest. This will become below.

## 2. THE UNIFORM, ISOTROPIC NOISE

If $r$ is the distance from $\mathbf{x}_1$ to $\mathbf{x}_2$, a particular of Eq. (5) is

$$\psi(r,\tau)=(2c/r)\int_{\tau-r/c}^{\tau+r/c}\psi_0(\sigma)d\sigma.$$

Equation (4) requires that

$$\psi_0(\sigma)=\psi_0(-\sigma),$$

and Eq. (3) that

$$\psi_0(\sigma)\leqslant\psi_0(0).$$

Since this solution depends only on $r$, it repres uniform, isotropic noise. The function

$$\psi_0(\tau)=\psi(0,\tau)=\langle p(\mathbf{x}t)p(\mathbf{x},t-\tau)\rangle,$$

is identified as the ordinary autocorrelation func the pressure at any point in space. Equation poses another restriction on $\psi_0$: if $\psi_0$ is integrab spectrum of the noise is

$$S(\omega)=4\int_0^\infty\psi_0(\tau)\cos\omega\tau d\tau,$$

and it may be proven that $S(\omega)\geq 0$ for all sequently, $\psi_0$ must be expressible as

$$\psi_0(\tau)=(1/2\pi)\int_0^\infty S(\omega)\cos(\omega\tau)d\omega,$$

with a positive spectrum, $S(\omega)$. Substituting Eq.

4),

$$)=(1/2\pi)\int_0^\infty S(\omega)j_0(\omega r/c)\cos(\omega\tau)d\omega, \qquad (17)$$

$$j_0(x)=(\sin x)/x$$

ical Bessel function of order zero.
ı. (10) and the condition $\psi_u(r,\infty)=0$, one

$$)(1/2\pi\rho c)\int_0^\infty S(\omega)j_1(\omega r/c)\sin(\omega\tau)d\omega, \qquad (18)$$

$_1-x_2$, etc. In the same way, Eq. (11) yields

$$1/2\pi\rho^2c^2)\int_0^\infty S(\omega)$$

$$\times j_1(\omega r/c)\cos(\omega\tau)d\omega/\omega$$

$$2\pi\rho^2c^2)\int_0^\infty S(\omega)j_2(\omega r/c)\cos(\omega\tau)d\omega, \qquad (19)$$

$$/r^2)(1/2\pi\rho^2c^2)\int_0^\infty S(\omega)$$

$$\times j_2(\omega r/c)\cos(\omega\tau)d\omega. \qquad (19')$$

the quantities defined above are determined, of the uniform isotropic noise, by its spec-
.

### IE UNIFORM, ANISOTROPIC NOISE

general solution of Eqs. (3) and (4) is

$$\int\int\int\Psi(\alpha,\beta,\gamma)$$

$$\times\cos(\alpha\xi+\beta\eta+\gamma\zeta-\omega\tau)d\alpha d\beta d\gamma, \qquad (20)$$

a real function and

$$\omega=(\alpha^2+\beta^2+\gamma^2)^{\frac{1}{2}}\geqslant 0. \qquad (21)$$

$\eta=\zeta=0$, one obtains

$$\tau)=(1/8\pi^3)\int\int\int\Psi\cos(\omega\tau)d\alpha d\beta d\gamma, \qquad (22)$$

polar coordinates

$$\alpha=(\omega/c)\sin\theta\cos\phi,$$
$$\beta=(\omega/c)\sin\theta\sin\phi, \qquad (21')$$
$$\gamma=(\omega/c)\cos\theta,$$

the spectrum of the noise is obtained in the form

$$S(\omega)=(\omega^2/4\pi^2c^3)\int\int\Psi\sin\theta d\theta d\phi; \qquad (23)$$

as before, $S(\omega)$ must be non-negative, which imposes a restriction on $\Psi(\alpha,\beta,\gamma)$. This is not the only restriction on the function $\Psi$, however. In fact, it is very probable that $\Psi$ must be non-negative for all $\alpha,\beta,\gamma$, but the proof of this hypothesis will not be attempted here.

The other correlation functions are obtainable from Eqs. (10) and (11):

$$\phi_u=(1/8\pi^3)\int\int\int(\alpha/\rho\omega)\Psi$$

$$\times\cos(\alpha\xi+\beta\eta+\gamma\zeta-\omega\tau)d\alpha d\beta d\gamma, \qquad (24)$$

$$\psi_{uv}=(1/8\pi^3)\int\int\int(\alpha\beta/\rho^2\omega^2)\Psi$$

$$\times\cos(\alpha\xi+\beta\eta+\gamma\zeta-\omega\tau)d\alpha d\beta d\gamma. \qquad (25)$$

The physical interpretation of $\Psi$ is seen by calculating the mean energy flow:

$$\langle up\rangle=(1/8\pi^3)\int\int\int(\alpha/\rho\omega)\Psi d\alpha d\beta d\gamma.$$

This suggests that $\Psi/\rho c$ is the density of energy associated with those waves whose propagation vector $\alpha,\beta,\gamma$ lies in $d\alpha d\beta d\gamma=\omega^2d\omega\sin\theta d\theta d\phi=f^2df\sin\theta d\theta d\phi$, $f$ being the frequency.

This interpretation is strengthened by considering the asymptotic expression[3] for Eq. (20):

$$16\pi^2c^2r\psi=\int_0^\infty\omega\Psi(\omega,\vartheta,\varphi)\sin[\omega(r/c-\tau)]d\omega$$

$$+\int_0^\infty\omega\Psi(\omega,\pi-\vartheta,\pi+\varphi)\sin[\omega(r/c-\tau)]d\omega, \qquad (20')$$

where

$$\xi=r\sin\vartheta\cos\varphi,\quad \eta=r\sin\vartheta\sin\varphi,\quad \zeta=r\cos\vartheta.$$

For sufficiently large $r$, therefore, the space correlation of $p$ is determined entirely by those sinusoidal components that travel in the same direction as, or in the opposite direction to, the vector $\xi,\eta,\zeta$.

If $\Psi(\omega,\vartheta,\varphi)$ is independent of $\vartheta$ and $\varphi$, Eq. (20′) becomes identical with Eq. (17) for isotropic noise, with

$$S(\omega)=\omega^2\Psi(\omega)/4\pi^2c^3.$$

---

. Morse, *Vibration and Sound* (McGraw-Hill Book c., New York, 1948), second edition, p. 316, for the ations between the $j_n$.

[3] This is valid for sufficiently regular $\Psi$ and large $r$; it is readily obtained by performing the integration over $\theta$ and $\phi$ by the method of stationary phase.

## 4. THE NOISE FIELD NEAR A REFLECTING PLANE

If the medium contains obstacles, the noise field cannot be homogeneous. The simplest obstacle is an infinite perfectly reflecting plane, at $z=0$. This may be either rigid ($w=0$ at $z=0$) or soft ($p=0$ at $z=0$). These boundary conditions on $p$ result in the following conditions on the correlation functions for the rigid plane:

$$\begin{aligned} &\text{at } z_1=0, \quad \psi_w(\mathbf{x}_1, \mathbf{x}_2, \tau)=0; \\ &\text{at } z_2=0, \quad \psi_w(\mathbf{x}_2, \mathbf{x}_1, \tau)=0; \\ &\text{at } z_1=z_2=0, \quad \psi_{ww}(\mathbf{x}_1, \mathbf{x}_2, \tau)=0; \end{aligned} \tag{26}$$

while for the soft plane,

$$\text{at } z_1 \text{ and/or } z_2=0, \quad \psi(\mathbf{x}_1, \mathbf{x}_2, \tau)=0. \tag{26'}$$

To complete the specification of $\psi$, it is also necessary to give its form at great distances from the reflector. It will be supposed that when

$$z_1 \text{ and/or } z_2 \rightarrow \infty, \quad \psi \rightarrow \psi_\infty(\xi, \eta, \zeta, \tau) = \psi_\infty(\xi, \eta, -\zeta, \tau), \tag{27}$$

and that

$$\psi_\infty(\xi, \eta, \infty, \tau)=0. \tag{27'}$$

The symmetry of $\psi_\infty$ in $\zeta$ requires explanation. It implies that $\Psi_\infty(\alpha, \beta, \gamma)=\Psi_\infty(\alpha, \beta, -\gamma)$, which means that the flux of energy toward the reflector is equal to the flux away, and that this balance exists for every direction and frequency. This is a reasonable physical requirement to include in the formulation of the problem.

The solution of the problem is then very simple: if $\zeta'=z_1+z_2$,

$$\psi=\psi_\infty(\xi, \eta, \zeta, \tau) \pm \psi_\infty(\xi, \eta, \zeta', \tau), \tag{28}$$

the positive sign applying to the rigid plane, the negative, to the soft plane.

If $\psi_\infty$ represents isotropic noise, the Eq. (28) indicates that, near the reflector, the noise will not be isotropic, and the nature of this anisotropy is clear.

## 5. THE RADIATION OF NOISE BY A VIBRATING PLANE

This problem will be simplified by neglecting the reaction of the medium on the motion of the plane, and assuming that at $z=0$,

$$w=\partial h(xyt)/\partial t, \tag{29}$$

$h$ being the displacement of the surface from the plane $z=0$. It will also be supposed that

$$\langle h(x_1y_1t)h(x_2y_2t-\tau)\rangle = H(\xi\eta\tau) \tag{30}$$

exists, is real, finite, and known, and that the appropriate boundary condition is

$$\psi_{ww}=-\partial^2 H/\partial\tau^2 \quad \text{at} \quad z_1=z_2=0. \tag{31}$$

In general it will be possible to represent $H$ by the Fourier integral

$$H(\xi\eta\tau)=(1/8\pi^3)\int\int\int Z(\alpha\beta\omega) \times\cos(\alpha\xi+\beta\eta-\omega\tau)d\alpha d\beta$$

(in which $\alpha$, $\beta$ run from $-\infty$ to $+\infty$, but $\omega$ o
0 to $\infty$). A solution is readily found as follows
Let

$$\kappa=(\alpha^2+\beta^2)^{\frac{1}{2}},$$

and define

$$\begin{aligned} \Gamma&=(\omega^2/c^2-\kappa^2)^{\frac{1}{2}}\geqslant 0, \quad \text{when} \quad \omega>\kappa c, \\ \mathrm{K}&=(\kappa^2-\omega^2/c^2)^{\frac{1}{2}}\geqslant 0, \quad \text{when} \quad \omega<\kappa c, \end{aligned}$$

so that Eqs. (4) and (5) are satisfied by

$$8\pi^3\psi=\int\int\int_{\omega>\kappa c} A(\alpha\beta\omega) \times\cos(\alpha\xi+\beta\eta+\Gamma\zeta-\omega\tau)d\alpha d\beta d\omega + \int\int\int_{\omega<\kappa c} B(\alpha\beta\omega)\cos(\alpha\xi+\beta\eta-\omega\tau) \times\exp(-\mathrm{K}\zeta')d\alpha d\beta$$

where $\zeta'=z_1+z_2$ as before. The Eq. (31) will be
satisfied if

$$\begin{aligned} A&=\rho\omega^4 Z/\Gamma^2, \\ B&=\rho\omega^4 Z/\mathrm{K}^2, \end{aligned}$$

but then the integrals of Eq. (34) will exist
$Z(\alpha, \beta, \kappa c)=0$, which seems like a very
restriction.

It is more profitable to consider the physical
of the function $Z$, than to obtain less restricti
tions. The Eq. (32) represents an analysis of the
of the boundary surface into sinusoidal running
propagation vector $\alpha$, $\beta$ and phase velocity $c_0=$
integration over $\omega$ is thus an integration over
is probably justified in some cases, when the
of the surface is caused by forces that are strong
lated over extensive areas. If the surface is th
elastic plate, however, and its vibration is ca
random local shocks of short duration, $Z$ will
strong peak near one value of $c_0=\omega/\kappa$, name
value which is the velocity of free flexural wave
plate. The problem can thus be further simpl
omitting the integration over $\omega$, but replacin
$c_0\kappa$. Then only one term of Eq. (34) will rema
high frequency one if $c_0>c$, and the low freque
if $c_0<c$. The case $c_0=c$ will rarely arise.

When $c_0<c$, and only the low frequency ter
no energy is radiated from the surface, and
turbance extends only a small distance ab
vibrating plane. The height of the disturbe
depends not on the amplitude of the vibratio

gth. It may also be noted that this is the hat arises in the case of an incompressible ). It appears that these low frequency sent a disturbance that is more analogous ce than to noise. However, since viscosity itted from these calculations, it is unlikely vill yield a complete theory of turbulence, jective "analogous" is therefore used ad- vill also be noted that both the form of these nd the condition $c_0<c$ are strongly remi- ne theory of total reflection.

nd $a^2=(c_0/c)^2-1$, the Eq. (34) reduces to

$$/a^2)\int\int \kappa^2 Z$$

$$\times\cos[\alpha\xi+\beta\eta+\kappa(a\zeta-c_0\tau)]d\alpha d\beta. \quad (36)$$

approximated by

$$/a^2)(\pi/2r)^{1/2}\int \kappa^{5/2}$$

$$\times[Z(\kappa\varphi)\cos\kappa(r+a\zeta-c_0\tau-\pi/4)$$

$$\kappa,\ \varphi+\pi)\cos\kappa(r-a\zeta+c_0\tau-\pi/4)]d\kappa, \quad (36.1)$$

$$\xi=r\cos\varphi,\quad \eta=r\sin\varphi,$$

proximation is valid when $r$ is sufficiently large. As might have been anticipated, the noise radiated from the vibrating surface is not isotropic.

The calculation of the energy flux at the radiating surface can be carried through as before. The result is that

$$8\pi^3\psi_w=(\rho c_0^3/a)\int\int \kappa^2 Z$$

$$\times\cos[\alpha\xi+\beta\eta+\kappa(a\zeta-c_0\tau)]d\alpha d\beta, \quad (37)$$

and the energy radiated, per unit area and time, is obtained by setting $\tau=0$, $\xi=\eta=\zeta=0$.

These considerations also apply to the emission of sub-audible sound waves by the sea surface. It has recently been suggested that such radiation is related to several observed phenomena.[4] In this case $c_0$ is a function of $\kappa$, given by

$$c_0^2=(g/\kappa)\tanh\kappa D\leqslant gD,$$

where $g$ is the acceleration of gravity and $D$ is the depth of the ocean. The radiation condition $c_0^2>c^2$ therefore implies

$$D\geqslant c^2/g=11\text{ km}$$

when $c$ is the velocity of sound in air. The mean depth of the oceans is only about 5 km, and even the narrow deeps do not exceed 11 km. It is therefore difficult to see how such radiation can occur.

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Fred B. Daniels, J. Acoust. Soc. Am. 24, 83 (1952).

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# Total Reflection of Waves from a Point Source*

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## I. *Introduction*

In this paper an analysis is made of the reflection of a pulse of sound from a point source in a non-absorbing liquid plane boundary, under the circumstance that the index of refraction is $<1$. The analysis is equally applicable to the total reflection of electromagnetic radiation from a vertical dipole, in the absence of absorption. The results clarify the mechanism of propagation of the head wave which has been observed in acoustic experiments. It is shown without approximation that a pulse is received in the first medium at a time corresponding to propagation along the surface with wave velocity of the second medium.

Under certain circumstances a pole in the complex plane of integration makes a contribution to the field at long distances. However the pole always lies on the imaginary axis for non-absorbing media, giving rise to an exponentially decreasing term at long distances. Thus no true (undamped) surface waves can occur. The contribution from this pole is absent in the electromagnetic case when, as is usual, the magnetic permeabilities of the two media are equal.

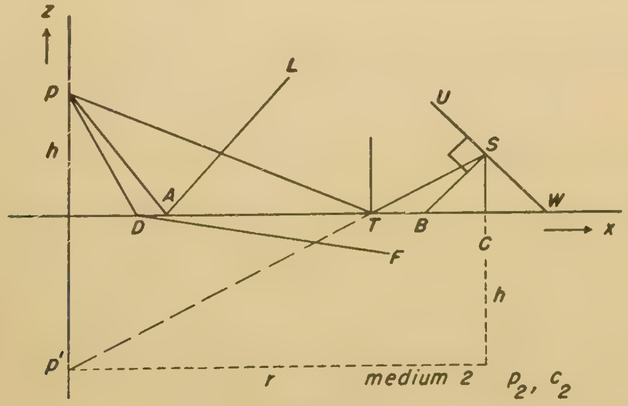

FIGURE 1

Figure 1 shows a point source at $P$, a height $h$ above an infinite plane

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surface separating two non-absorbing media. The wave velocity is greater in medium 2 than in medium 1. The signal is received at $S$, a height $z$ above the bounding surface.

Let the source be harmonic, of circular frequency $\omega$. In the acoustic case, when both media are liquids, the acoustic potentials $\phi_1$ and $\phi_2$ satisfy in their respective media

$$\begin{aligned} \Delta\phi_1 + k_1^2\phi_1 &= 0, \\ \Delta\phi_2 + k_2^2\phi_2 &= 0 \end{aligned} \tag{1}$$

with the boundary conditions, on the plane $z = 0$

$$\begin{aligned} \rho_1\phi_1 &= \rho_2\phi_2 , \\ \frac{\partial\phi_1}{\partial z} &= \frac{\partial\phi_2}{\partial z}. \end{aligned} \tag{2}$$

In these equations $\rho$ denotes density, $c$ wave velocity, and $k = \omega/c$.

In the electromagnetic case, when both media are non-conducting, and the source is a vertical dipole, the Hertz potentials $\pi_1$ and $\pi_2$ satisfy [1]

$$\begin{aligned} \Delta\pi_1 + k_1^2\pi_1 &= 0, \\ \Delta\pi_2 + k_2^2\pi_2 &= 0 \end{aligned} \tag{3}$$

with the boundary conditions, on the plane $z = 0$

$$\begin{aligned} \frac{k_1^2}{\mu_1}\pi_1 &= \frac{k_2^2}{\mu_2}\pi_2 , \\ \frac{\partial\pi_1}{\partial z} &= \frac{\partial\pi_2}{\partial z} . \end{aligned} \tag{4}$$

In equation (4) $\mu$ is the magnetic permeability. It will be noticed that when $\mu_1 = \mu_2$ the electromagnetic problem is less general than the acoustic, since the ratio of the coefficients of $\pi_1$ and $\pi_2$ in the first of equations (4) is $k_1^2/k_2^2 = c_2^2/c_1^2$, whereas $\rho_1/\rho_2$ is independent of $c_1/c_2$.

The field in medium 2 has been discussed previously [2], in this paper the field in medium 1 will be analyzed. In the main our results confirm those of previous investigators [3] but some new features are introduced, to wit: *(1)* The time of arrival of a pulse is evaluated exactly, and shown to agree with the conclusions inferred from the approximate evaluation of the field from a harmonic source. *(2)* The validity of the method of steepest descents in this problem is examined by evaluating the next higher approximation, and a number of the conditions for the validity of the method are shown to have simple and natural physical interpretations. The amplitude dependence of the head wave is also iven a simple geometrical interpretation. The head wave denotes the wave vhich in the region of total reflection arrives before the reflected wave, and may rrive before the directly transmitted wave.[1] (3) Under certain circumstances pole lying on the imaginary axis in the complex plane of integration makes a ontribution to the field, yielding an exponentially damped wave at long dis- ances in medium 1. The circumstances are such that the pole makes no contri- ution in the electromagnetic case when $\mu_1 = \mu_2$. The contribution of this pole loes not seem to have been previously remarked.[2]

## II. *Notation and Basic Formulas*

We employ our previous notation: the acoustic potential at $S$ (Figure 1) vith the coordinates $(x,y,z)$ is

$$\phi_1 = \phi_0 + \phi_r = \frac{\exp\{ik_1R\}}{R} + \phi_r\,, \tag*{5)}$$

is the distance $PS$ (Figure 1), and the reflected wave $\phi_r$ is

$$\phi_r = ik_1 \int_0^\infty du\, \frac{u}{\sqrt{1-u^2}}\, f_r J_0(k_1ru) \exp\{ik_1(z+h)\sqrt{1-u^2}\}, \tag*{6)}$$

$$f_r = \frac{\beta\sqrt{1-u^2} - \sqrt{\alpha^2-u^2}}{\beta\sqrt{1-u^2} + \sqrt{\alpha^2-u^2}}. \tag*{7)}$$

n equations (6) and (7), $r = (x^2+y^2)^{1/2}$, $\alpha = c_1/c_2$ is assumed $<1$, $\beta$ equals $_2/\rho_1$ (acoustic) or $\mu_1\alpha^2/\mu_2$ (electromagnetic), and may have any positive value. quation (7) for the reflection coefficient $f_r$ is equation (10) of reference 2. quation (6) follows readily from equation (6) of reference 2 by the procedure sed to obtain equation (13) of reference 2. Details of the derivation of equa- ion (6) are also given by Ott [3]. The correct behavior of the solution at in- inity in either medium is guaranteed by choosing $\sqrt{\alpha^2-u^2}$ and $\sqrt{1-u^2}$

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[1] Such early arriving waves have been observed in geophysical prospecting by explosive ounds (cf. Muskat, ref. 3), and, in underwater propagation by J. L. Worzel and M. Ewing, *xplosion sounds in shallow water*, Geol. Soc. of Am., Memoir 27, 1948.

[2] Of the authors listed in reference 3, Lamb solved not the problem under consideration ere, but some related problems. Jeffreys uses operational methods throughout. Muskat btained a valid formal solution, but evaluated the resultant integrals by means of a relatively rude approximation. Ott's analysis parallels our own but he does not follow the steepest escent contours in the complex plane with the care which we have used. In essence our valuation of the integrals confirms Ott's results, but extends them by including the small but heoretically interesting contributions from the pole. Kruger evaluated the integrals without sing the method of steepest descents, for the electromagnetic case. However, his analysis immediately applicable to total reflection only when $h = 0$, and uses the restrictive assump- ion that $\mu_1 = \mu_2$. Brehovskih's work, in Russian, seems to parallel ours, but he makes no ention of the pole.

positive real for small positive $u$ and positive imaginary for large positive $u$. The choice of sign is achieved by drawing the cuts through $\alpha$ and 1 upward, as shown in Figure 2. It will prove convenient to draw the cuts through $-\alpha$ and $-1$ downward as shown; for the purposes of this section their directions are not significant. The contour of equation (6) runs from 0 to $\infty$ on the real axis without crossing any of the cuts. For $z+h > 0$

$$\frac{\exp\{ik_1\sqrt{r^2+(z+h)^2}\}}{\sqrt{r^2+(z+h)^2}} \tag{8}$$
$$= \int_0^\infty dt\, \frac{t}{\sqrt{t^2-k_1^2}} J_0(rt) \exp\{-(z+h)\sqrt{t^2-k_1^2}\}.$$

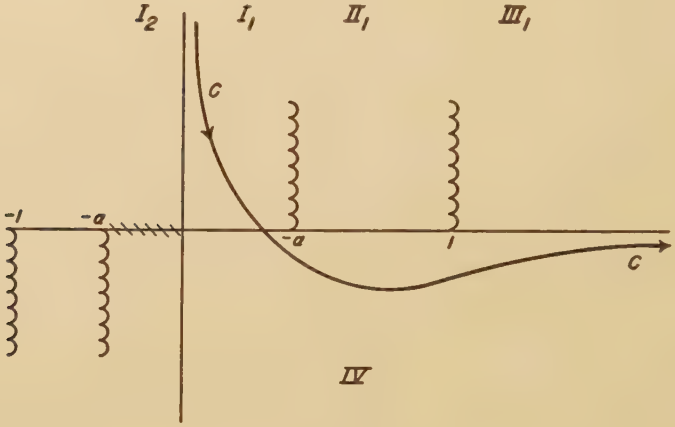

FIGURE 2

Equation (8) is well known; it implies that the real part of $\sqrt{t^2 - k_1^2}$ is always $>0$ on the contour, (cf. Stratton [5]) or equivalently, that the contour passes below the singularity at $t = k_1$ (cf. Watson [6]). Letting $t = k_1 u$ in equation (8), remembering $k_1 > 0$, and noting that $\sqrt{u^2 - 1} = -i\sqrt{1 - u^2}$ is consistent with the definitions of the signs of the radicals in equations (6) and (8), it can be seen that

$$\phi_1 = \phi_0 + \phi_s + \phi_t\,, \tag{9}$$

$$\phi_s = \frac{e^{ik_1 d}}{d}\left[\frac{\beta(z+h)/d - \sqrt{\alpha^2 - \tau^2}}{\beta(z+h)/d + \sqrt{\alpha^2 - \tau^2}}\right], \tag{10}$$

$$\phi_t = 2ik_1 \int_0^\infty du\, \frac{u}{\sqrt{1-u^2}} F(u) J_0(k_1 r u) \exp\{ik_1(z+h)\sqrt{1-u^2}\}, \tag{11}$$

$$F(u) = \frac{\sqrt{\alpha^2 - \tau^2}}{\beta\sqrt{1 - \tau^2} + \sqrt{\alpha^2 - \tau^2}} - \frac{\sqrt{\alpha^2 - u^2}}{\beta\sqrt{1 - u^2} + \sqrt{\alpha^2 - u^2}}, \tag{12}$$

$$d = \sqrt{r^2 + (z + h)^2}, \qquad \tau = r/d, \qquad \sqrt{1 - \tau^2} = \frac{z + h}{d}. \tag{13}$$

The distance between the receiver and the image of the source is $d = P'S$ (Figure 1); $\tau$ is the sine of the angle of incidence $TPP'$ (Figure 1). In equation (7) $u$ equals the sine of the angle of incidence (see [2]); equations (6) and (11) are integrals over real and complex angles of incidence. The amplitude and phase of $\phi_s$ are precisely those expected for a spherical wave propagating along the geometrically reflected ray $PTS$ (Figure 1), if we assume this wave to be reflected with the plane wave coefficient of equation (7), with $u = \tau$. The sign of $\sqrt{\alpha^2 - \tau^2}$ is identical with that of $\sqrt{\alpha^2 - u^2}$ when $u = \tau$. We infer therefore that all deviations from ray or geometrical propagation are contained[3] in the term $\phi_t$.

The poles of the integrand of equation (11) lie at the roots of

$$\beta\sqrt{1 - u^2} + \sqrt{\alpha^2 - u^2} = 0 \tag{14}$$

or at

$$\begin{aligned} u &= \pm\left(\frac{\beta^2 - \alpha^2}{\beta^2 - 1}\right)^{1/2}, && 1 < \beta, \\ u &= \pm i\left(\frac{\beta^2 - \alpha^2}{1 - \beta^2}\right)^{1/2}, && \alpha < \beta < 1, \\ u &= \pm\left(\frac{\alpha^2 - \beta^2}{1 - \beta^2}\right)^{1/2}, && \beta < \alpha. \end{aligned} \tag{15}$$

In that part of the complex plane which is above the real axis, we denote by I the region to the left of the cut at $\alpha$, by II the region between the cuts at $\alpha$ and 1, and by III the region to the right of the cut at 1. Since the cuts may (and will later) be drawn so that they intersect the positive imaginary axis, we further distinguish between region $\mathrm{I}_1$, containing those points in region I which lie in the first quadrant of the complex plane, and $\mathrm{I}_2$, containing those points in region I which lie in the second quadrant, and similarly for regions II and III. The fourth quadrant is designated by IV. Some of these regions are shown in Figure 2. In regions $\mathrm{I}_1$, $\mathrm{I}_2$, $\mathrm{II}_1$, $\mathrm{III}_1$, and IV the real and imaginary parts of $(1 - u^2)^{1/2}$, $(\alpha^2 - u^2)^{1/2}$, and $u/(1 - u^2)^{1/2}$ are negative in the following regions:

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[3] This formulation, in which $\phi_t = 0$ in the geometrical limit $k_1 \to \infty$ appears more logical than the customary procedure of ignoring the dependence on $\alpha$, $\beta$, and angle of incidence of the reflection coefficient, whereby the field in medium 1 is regarded as the sum of spherical waves radiating from sources of equal strength at $P$ and $P'$ (Figure 1), plus a contour integral, which integral is not zero in the geometrical limit. Cf. Stratton, *op. cit.*, p. 573 ff., or Ott, *op. cit.*

$$
(16)\qquad
\begin{aligned}
\mathcal{R}e\,(1-u^2)^{1/2} &< 0: && \mathrm{III}_1\\
\mathcal{I}m\,(1-u^2)^{1/2} &< 0: && \mathrm{I}_1\,,\ \mathrm{II}_1\\
\mathcal{R}e\,(\alpha^2-u^2)^{1/2} &< 0: && \mathrm{II}_1\,,\ \mathrm{II}_2\,,\ \mathrm{III}_1\\
\mathcal{I}m\,(\alpha^2-u^2)^{1/2} &< 0: && \mathrm{I}_1\,,\ \mathrm{II}_2\\
\mathcal{R}e\,u/(1-u^2)^{1/2} &< 0: && \mathrm{I}_2\,,\ \mathrm{II}_2\,,\ \mathrm{III}_1\\
\mathcal{I}m\,u/(1-u^2)^{1/2} &< 0: && \mathrm{III}_1\,,\ \mathrm{IV}.
\end{aligned}
$$

Otherwise they are positive. The real and imaginary parts of the radica change sign discontinuously at the cuts but become zero on the real or on the imaginary axis if they change sign crossing it.

Equations (16) show there are no roots of equation (14) in region IV. Consequently, as shown for similar integrals by Muskat and Ott [3] we obtain

$$(17)\qquad \phi_t = ik_1 \int_C du\, \frac{u}{\sqrt{1-u^2}}\, F(u) H_0^{(1)}(k_1 ru) \exp\{ik_1(z+h)\sqrt{1-u^2}\}.$$

The contour $C$ of equation (17) runs from $i\infty$ to $\infty$ on the real axis, as shown i Figure 2. Replacing $H_0^{(1)}$ by its asymptotic expansion, equation (17) become

$$(18)\qquad \phi_t = \left(\frac{2k_1}{\pi r}\right)^{1/2} e^{i\pi/4} \int_C du \left(\frac{u}{1-u^2}\right)^{1/2} F(u) \exp\{ik_1 A(u)\},$$

$$(19)\qquad A(u) = (z+h)\sqrt{1-u^2} + ru.$$

In equation (17) $-\pi < \arg u \leq \pi$. To prevent circling the singularity at th origin, the cut at $-\alpha$ is extended to the origin along the negative real axis a indicated by the stippling in Figure 2.

We evaluate $\phi_t$, equation (18), by the method of steepest descents.[4] Ther are two distinct cases: $\tau < \alpha$, considered in the immediately following sectio and $\tau > \alpha$, which is deferred to section IV.

## III. *Solution for* $\tau < \alpha$

The saddle points of the integral (18) lie at the roots $u = \pm\tau$ of the equation $A'(u) = 0$, with

$$(20)\qquad A'(u) = r - \frac{(z+h)u}{\sqrt{1-u^2}}.$$

We shall be concerned only with the point $u = \tau$, which for $\tau < \alpha$ lies in $\mathrm{I}_1$ $A(u)$ is pure real on the real axis between 0 and 1, and, in $\mathrm{I}_1$, has a maximu at $u = \tau$. Along the contour $\mathcal{R}e\, A(u) = A(\tau)$ through $u = \tau$ in $\mathrm{I}_1$, $\mathcal{I}m\, A($

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[4] Watson, *op. cit.*, p. 2.

can have no maxima and but a single minimum, at $u = \tau$. Evaluation of $\phi_t$, equation (18), by the method of steepest descents now proceeds in the usual way. To completely justify the analysis however it is necessary[5] to make sure that it is possible to deform the contour $C$ of Figure 2 into the contour $\mathcal{R}e\, A(u) = A(\tau)$ passing through $u = \tau$ in $\text{I}_1$.

The argument required is similar to that employed previously. Use is made of equations (16) and (20), together with the remark that the contour is parallel to the imaginary (real) axis if and only if $A'(u)$ is pure real (imaginary). If $u = \rho e^{i\theta}$, then in $\text{III}_1$ and IV, for large $\rho$

$$A(u) = \rho\{[r \cos \theta - (z + h) \sin \theta] + i[(z + h) \cos \theta + r \sin \theta]\} \tag{21}$$

while in $\text{I}_1$ and $\text{I}_2$, for large $\rho$

$$A(u) = \rho\{[r \cos \theta + (z + h) \sin \theta] + i[r \sin \theta - (z + h) \cos \theta]\}. \tag{22}$$

It can be seen from equation (16) that the only roots of equation (14) which can possibly concern us lie in region II. We can conclude that the contour $C$ can be deformed into the contour $\mathcal{R}e\, A(u) = A(\tau)$, which we denote by $C'$ (Figure 3), without crossing any poles.

We recall that $u$ is to be interpreted as the sine of the angle of incidence of an arbitrary ray from the source. The equation $u = \tau$ for the saddle point of

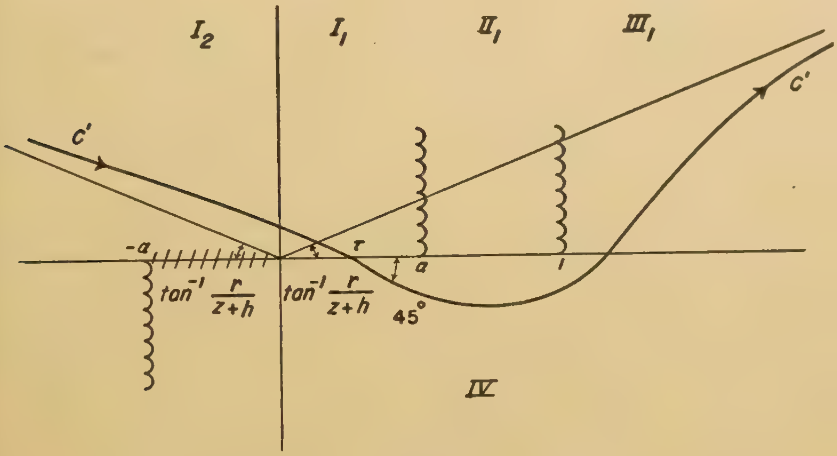

FIGURE 3

equation (18) corresponds therefore to the assertion that the *deviations* from ray propagation are in this case, $\tau < \alpha$, determined primarily by radiation along the direction of the expected geometrical path. This interpretation is confirmed by the fact that $\exp \{ik_1A(\tau)\} = \exp \{ik_1d\}$ is a phase factor common to $\phi_s$, equation (10), and to this estimate of $\phi_t$. Moreover since $F(u) = 0$ at $u = \tau$,

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[5] This point has not always been sufficiently emphasized.

$\phi_t$ is seen to be small compared to $\phi_s$ (in the limit of high frequencies and large distances, where the method of steepest descents is applicable). These results are in complete agreement with those of Ott [3].

## IV. *Solution for* $\tau > \alpha$

When $\tau > \alpha$ it is necessary to deform the contour into the shape $C_1$ followed by $C_2$ of Figure 4 in order to obtain a convergent contour integral through the saddle point $u = \tau$. We write

$$\phi_t = \phi_t(C_1) + \phi_t(C_2) \tag{23}$$

where $\phi_t$ is given by equation (17), and both $\phi_t(C_1)$ and $\phi_t(C_2)$ are given by equation (17) with the substitution of $C_1$ or $C_2$ for $C$. Replacing $H_0^{(1)}$ by its asymptotic expansion, $\phi_t(C_2)$ is given by equation (18) with $C_2$ instead of $C$.

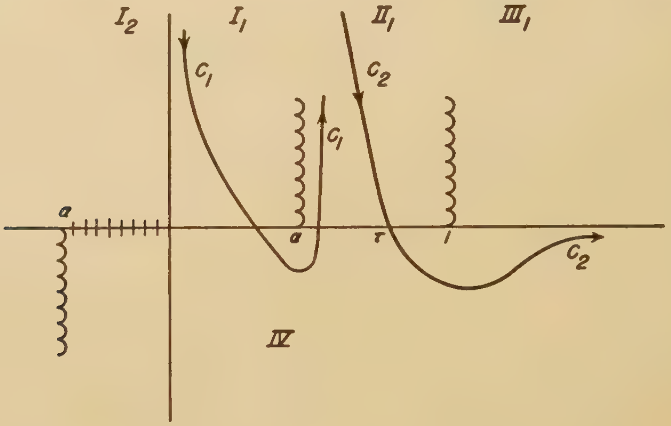

FIGURE 4

Since $\sqrt{\alpha^2 - u^2}$ does not occur in $A(u)$ the argument in the preceding section concerning the determination of the contour $\mathcal{Re}\, A(u) = A(\tau)$ is wholly unchanged, except for the fact that the contour extends to infinity on the left in $\mathrm{II}_2$ instead of $\mathrm{I}_2$. The only question to be settled is whether deformation of the contour requires crossing any of the poles in II. This question will be considered below. Except for possible contributions from poles in II the integral $\phi_t(C_2)$ is seen to yield precisely the same results as did $\phi_t$ in the preceding section. The contour into which $C_2$ is deformed is termed $C_2'$.

We proceed to $\phi_t(C_1)$: The first term in $F(u)$, equation (12), is merely a constant. Referring to equation (17) and to Figure 4, it is evident that in $\phi_t(C_1)$ the contour $C_1$ can be closed at infinity for this first term in $F(u)$, since the integral containing this term contains no terms involving $\sqrt{\alpha^2 - u^2}$. Nor does it contain any poles. Consequently the first term in $F(u)$ results in a vanishing integral and we have

$$\phi_\iota(C_1) = -ik_1 \int_{C_1} du \, \frac{u}{\sqrt{1-u^2}} \, \frac{\sqrt{\alpha^2-u^2}}{\beta\sqrt{1-u^2}+\sqrt{\alpha^2-u^2}} \tag{24}$$
$$\cdot \exp\{ik_1(z+h)\sqrt{1-u^2}\}H_0^{(1)}(k_1ru).$$

In II$_1$ the contour $C_1$ lies along the cut. The contour $C_1$ can be deformed so as to lie along the cut in I$_1$, since there are no poles in I$_1$. Because the integrand in equation (24) vanishes at $u = \alpha$ the integral around a small circle about $u = \alpha$ is zero. It follows that

$$\phi_\iota(C_1) = -2ik_1 \int_{C_b} du \, \frac{u\sqrt{\alpha^2-u^2}}{\beta^2(1-u^2)-(\alpha^2-u^2)} \tag{25}$$
$$\cdot \exp\{ik_1(z+h)\sqrt{1-u^2}\}H_0^{(1)}(k_1ru).$$

In equation (25) the contour $C_b$ runs in II$_1$ along the cut, starting at $u = \alpha$ and going to infinity.

We desire the "best" contour for the branch line integral $\phi_\iota(C_1)$; namely a contour which appears likely to minimize the error. Although no saddle point can be found for $\phi_\iota(C_1)$, it is very reasonable to deform $C_1$ into a contour along which the phase of the integrand remains constant. Such a steepest descent contour, whether or not it passes through a saddle point, still seems least likely to introduce complicating cancellations and reinforcements, particularly in the large $k_1r$ limit (in which we are ultimately going to be most interested).

Consequently an approximate expression for $\phi_\iota(C_1)$ is obtained much as before by replacing $H_0^{(1)}$ in equation (25) by its asymptotic expansion, and determining the contour $\mathcal{R}e\, A(u) = A(\alpha)$ into which the cut through $\alpha$ must be deformed. Only if this deformation of the contour requires crossing any of the poles in II must their contributions be considered.[6] The contour $\mathcal{R}e\, A(u) = A(\alpha)$, which we term $C_1'$, is shown in Figure 5 where the cut through $\alpha$ has been deformed so that it coincides with $C_1'$. The deformation is justified as in the preceding section. The integral along $C_1'$ is computed, as in the method of steepest descents, by expanding the integrand about the point $u = \alpha$. The final result is an expression for the head wave:

$$\phi_\iota(C_1') = \frac{2\alpha i}{k_1\beta(1-\alpha^2)^{1/4}} \, \frac{e^{ik_1\psi}}{r^{1/2}[r(1-\alpha^2)^{1/2}-(z+h)\alpha]^{3/2}} \tag{26}$$

and

$$\psi = (z+h)\sqrt{1-\alpha^2}+r\alpha. \tag{27}$$

---

[6] It is definitely not correct to try to evaluate the integral along an arbitrary contour between $\alpha$ and $\infty$. The exact value of the integral is independent of the choice of contour, of course. But because the integral is not evaluated exactly, the estimated value of the integral can depend on the choice of contour, as apparently happens in the Sommerfeld problem. T. Kahan and G. Eckart, Jour. Phys. Rad., *10*, 165 (1949) and Phys. Rev., *76*, 406 (1949).

Equation (26) shows that in the limit of high frequencies and large distances the amplitude of $\phi_t(C_1')$ is small compared to $\phi_s$, equation (10). This was to be expected, since $\phi_t(C_1')$ is part of the deviation from geometrical propagation.

We return to the problem of whether or not poles are crossed. It is apparent from the above discussion that we might just as well have deformed the contours to $C_1'$ and $C_2'$ before replacing $H_0^{(1)}$ by its asymptotic expansion. Figure 5 illustrates some intermediate stages in the deformation of the contour $C$ of Figure 2 into integrals along $C_1'$ and $C_2'$ and shows the cuts through $u = -\alpha$ and $u = 1$. The contour $C_1'$ coincides with the cut through $\alpha$ and is drawn stippled, as is the cut from $u = -\alpha$ to $u = 0$. The portion of $C_2'$ to the left of $u = \tau$ is also shown. Regions I$_1$ and I$_2$ lie below and to the left of $C_1'$. In Figure 5 the contour $C$ has been bent around into region II between $C_1'$ and $C_2'$, but has not yet been extended to infinity. The dotted line is a deformation of $C$ which has not crossed the imaginary axis.

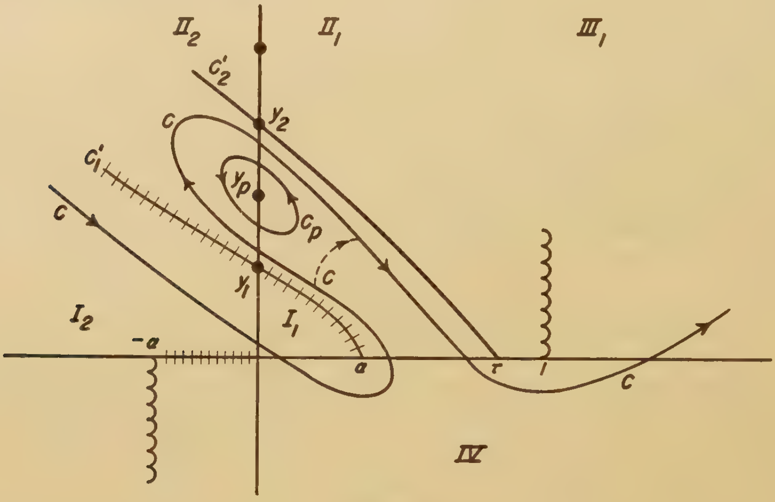

FIGURE 5

Referring to equation (15) it is clear that if $1 < \beta$ it is possible to extend to $C$ in Figure 2 to the dotted $C$ in Figure 5 to the solid $C$ in Figure 5 and so on to infinity in II$_2$, without crossing any poles. When $\beta < \alpha$ the poles lie on the real axis between $-\alpha$ and $\alpha$ *in region II*. Thus $C$ can again be deformed to infinity in II without crossing a pole. For $\alpha < \beta < 1$ the poles lie on the imaginary axis; the only root of significance is the positive imaginary root in II. Let $u = iy_1$ $(iy_2)$ at the intersection of $C_1'$ $(C_2')$ with the imaginary axis. If the pole lies at $y_p > y_2$ (Figure 5), the contour can obviously be deformed from the dotted $C$ to the solid $C$ without crossing the pole, and so on to infinity. If the ordinate of the pole is $< y_1$, the pole lies below the cut $C_1'$, and is again never crossed. The only case that remains is $\alpha < \beta < 1$, $y_1 < y_p < y_2$, as illustrated in Figure 5. In this case the contour cannot be extended from the dotted $C$ to the solid $C$ without crossing the pole, so that to the integral along the solid $C$ must be added the integral around the closed loop surrounding $y_p$ ; this integral readily yields

$$\phi_\iota(p) = 4ik_1\beta^2 \frac{(1-\alpha^2)^{1/2}}{(1-\beta^2)^{1/2}} \exp \{ik_1[(z+h)(1-\alpha^2)^{1/2}/(1-\beta^2)^{1/2}]\} \cdot K_0[k_1 r(\beta^2-\alpha^2)^{1/2}/(1-\beta^2)^{1/2}]. \tag{28}$$

$\phi_\iota(p)$ is the contribution from the pole and in this case where $\alpha < \beta < 1$, $y_1 < y_p < y_2$ we have

$$\phi_\iota(C_1) = \phi_\iota(p) + \phi_\iota(C_1') \tag{29}$$

where $\phi_\iota(C_1')$ is still given by equation (26). In equation (28), $K_0$ is the modified Hankel function. The condition $y_1 < y_p < y_2$ can be written as

$$(1-\alpha^2)^{1/2} + \frac{r\alpha}{z+h} < \left(\frac{1-\alpha^2}{1-\beta^2}\right)^{1/2} < \frac{d}{z+h}. \tag{30}$$

We have been unable to interpret $\phi_\iota(p)$ physically. Since for large $x$

$$K_0(x) \sim \left(\frac{\pi}{2x}\right)^{1/2} e^{-x} \tag{31}$$

$\phi_\iota(p)$ decreases exponentially for large $r$, and therefore can hardly be interpreted as a surface wave in this problem which neglects absorption, despite the $r^{-1/2}$ spreading factor inferred from equations (28) and (31). It is likely that at large distances the magnitude of $\phi_\iota(p)$ is small compared to the *error* made in deriving equation (26). It is possible that $\phi_\iota(p)$ is a portion of the difference between the accurate and asymptotic value of $\phi_\iota(C_1)$, or it may be a spurious result of the analysis. All that can be said is that our choice of "best" contour $C_1'$ leads naturally to $\phi_\iota(p)$ when $\alpha < \beta < 1$ and equation (30) is satisfied. In the electromagnetic case when $\mu_1 = \mu_2$, we have $\beta = \alpha^2$, so that $\alpha < \beta < 1$ is not possible under these circumstances.

## V. *Geometrical Interpretation*

In this section we assume the head wave propagates from $P$ to $S$ along the path $PABS$ (Figure 1) with velocity $c_2$ along $AB$, and show that this assumption leads to simple geometrical interpretations of the results of the preceding sections.

In Figure 1

$$AB = r - \frac{(z+h)\alpha}{\sqrt{1-\alpha^2}}. \tag{32}$$

Muskat [3] has pointed out that the phase difference between $P$ and $S$ corresponds to the assumed propagation, i.e., referring to Figure 1, that

$$k_1(PA) + \alpha k_1(AB) + k_1(BS) = k_1\psi \tag{33}$$

holds with $\psi$ given by equation (27). He also remarks that $PABS$ is a path of least time, in the sense of Fermat's principle. The surfaces of constant phase $\psi$ = constant intersect the $x,z$-plane of Figure 1 in lines parallel to $USW$ and perpendicular to $BS$. The wave fronts, obtained by rotating $USW$ about the $z$-axis, are obviously cones with axis $OP$. These cones have an angle $= \sphericalangle CSW =$ the complement of the critical angle.

Consider the two neighboring rays $BS$ and $B'S'$ intersecting the wave front $USW$ (Figure 6). Rotate the section $BSS'B'$ about $OP$. All the energy lying within the volume formed thereby which in unit time crosses the surface formed by rotating $SS'$ ultimately crosses the surface formed by rotating $VV'$, $V$ and $V'$ being intersections of $BS$ and $B'S'$ with the neighboring plane of constant phase $U'VW'$. Calling the pressure at $S$ $p(r,z)$ and at $V$ $p(r+dr,z+dz)$ and noting that $SS' = VV'$ we have

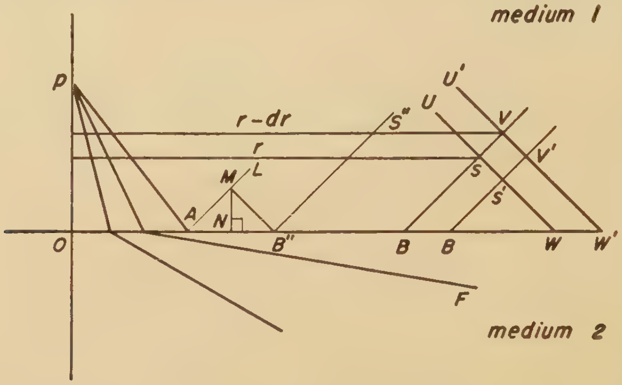

FIGURE 6

$$2\pi r p^2(r,z) = 2\pi(r+dr)p^2(r+dr,z+dz). \tag{34}$$

Equation (34) implies that for points on the same ray $BS$, $p$ is proportional to $r^{-1/2}$ and independent of $z$. This is precisely the result yielded by equation (26) from which, using equation (32), $\phi_\iota(C_1')$ is proportional to $(AB)^{-3/2}r^{-1/2}$.

Clearly equation (26) becomes grossly inaccurate[7] as $AB$ approaches zero length, since the solution must be finite at all points other than $P$. In Figure 6, $S''$ is a point in the field receiving the head wave via the ray $B''S''$. $B''M$ is the wave front starting at $B''$. It terminates abruptly at $M$, since the critical ray $PA$ is reflected into $AML$ and since there is no refracted wave along the surface to contribute to the head wave at points on the surface closer to the origin $O$ than $A$. We may expect our assumption of propagation along $PABS$ to be valid, and equation (26) to be a good approximation, as long as $B''M$ subtends a large number of Fresnel zones constructed from point $S''$. In other words it is necessary that

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[7] Brehovskih, see [3], by a different method obtained instead of equation (26) a modified expression which he claims accurately represents $\phi_\iota(C_1')$ for small or zero values of $AB$.

$$\frac{S''M - S''B''}{\lambda} \gg 1 \tag{35}$$

when $S''B'' \gg MB''$; equation (35) simplifies to

$$(1 - \alpha^2)(AB)^2 \gg 2\lambda z/\sqrt{1 - \alpha^2}. \tag{36}$$

Equation (26) is the leading term in an asymptotic expansion of $\phi_t(C_1)$, presumably valid in the limit as $k_1 r \to \infty$. For finite $k_1 r$ the ratio of the next term in the asymptotic expansion to the leading term, equation (26), furnishes an estimate of the error made in using equation (26) to represent the head wave. In[8] equation (25)

$$H_0^{(1)}(k_1 ru) = \left(\frac{2}{\pi k_1 ru}\right)^{1/2} \exp\,\{i(k_1 ru - \pi/4)\}\left(1 + \frac{\Delta}{8ik_1 ru}\right) \tag{37}$$

where $|\,\Delta\,| \leq 1$. If in equation (25), we ignore the term in $\Delta$, introduce the new variable $\eta$ which runs from 0 to $\infty$ as $u$ traverses $C_1'$ from $\alpha$ to $\infty$, and expand the terms in the integrand exclusive of the exponential terms in a power series, we obtain

$$\begin{aligned} \phi_t(C_1') = \frac{4i\alpha k_1^{1/2} d^{3/2}}{\pi^{1/2}\beta(1 - \alpha^2)^{1/4}} \frac{e^{ik_1\psi}}{r^{1/2}[r(1 - \alpha^2)^{1/2} - (z + h)\alpha]^{3/2}} \\ \cdot \int_0^\infty d\eta\, e^{-\eta k_1 d} \eta^{1/2}(1 + i\eta\delta + \cdots). \end{aligned} \tag{38}$$

The leading term in equation (38) yields equation (26). In equation (38) $\delta = \sum_j \delta_j$, $j = 1$ to 4, where the $\delta_j$ are defined as follows: For $j = 1$ to 3,

$$Q_j = B_j[1 + \delta_j(i\eta) + \cdots] \tag{39}$$

the functions $Q_j$, $j = 1$ to 3, being respectively $u^{1/2}$, $[\beta^2(1-u^2) - (\alpha^2-u^2)]^{-1}$, and $-idu/d\eta$. $\delta_4$ is defined by

$$(\alpha^2 - u^2)^{1/2} = B_4\eta^{1/2}[1 + \delta_4(i\eta) + \cdots]. \tag{40}$$

In equations (39) and (40) the $B_j$, $j = 1$ to 4, are numerical coefficients.

In equation (38) the absolute value of the ratio of the term in $\delta$ to the leading term is $3\delta/(2k_1 d)$, which must be $\ll 1$ if equation (26) is to be accurate. The expression $3\delta/(2k_1 d)$ where two or more of the $3\delta_j/(2k_1 d)$ are large can sometimes be made $\ll 1$ by cancellation; such cancellation is seldom possible in the omitted term of equation (38), of order $\eta^2$ in the integrand, whose ratio to the leading term will be $\sim \delta_i^2(k_1 d)^2$. We conclude therefore that it is probably necessary that each of the $3\delta_j/(2k_1 d)$ be $\ll 1$, in order that equation (26) be accurate.

The inequality corresponding to $j = 3$ is

$$\frac{3(z + h)}{2(1 - \alpha^2)^{3/2} k_1 (AB)^2} \ll 1. \tag{41}$$

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[8] Watson, *op. cit.*, p. 219.

It is a confirmation of our geometrical interpretation that equation (41) is equivalent to equation (36). Apparently the geometrical approximations involved in deriving equation (36) implied $z \gg h$. That the right hand side of equation (36) should depend on $(z + h)$ can be inferred from equations (6) and (11) which show that $\phi_r$ and $\phi_t$ are functions of $z$ and $h$ only through the sum $(z + h)$.

We may add that in equation (25) the contribution of the term in $\Delta$ can be estimated by expending that term in a power series about $u = \alpha$, leading to the inequality $8k_1 r\alpha \gg 1$, a typical condition for the validity of geometrical propagation. Some of the inequalities $3\delta_i/(2k_1 d) \ll 1$ imply

$$\frac{3}{4}\frac{r}{\alpha k_1 (AB)^2} \ll 1. \tag{42}$$

We have not interpreted equation (42). It can be inferred from $3\delta_i/(2k_1 d) \ll 1$ that $(1 - \alpha^2)$ and $\beta$ must not be too close to zero, conditions to be expected from equation (26), since $\phi_t(C_1)$ cannot increase indefinitely as $(1-\alpha^2)$ and $\beta$ approach zero.

## VI. *Solution for Complex* ω

To this point we have been concerned with positive real $k_1$ and $k_2$. To determine the received signal resulting from a pulse, we require the solutions for complex values of $\omega$, where $\mathscr{I}m\ \omega \geq 0$. We retain $k_1 = \omega/c_1$, $k_2 = \omega/c_2$, $c_1$ and $c_2$ real. The previously adopted means of obtaining the solution, based on the expansion of $e^{ikR}/R$ in plane waves as first used by Weyl [7], would in the present case[9] involve divergent integrals. We can follow Sommerfeld [8] however; by analytic continuation it can be seen that equation (8) is correct with $(h + z) > 0$, in the extended range $r \geq 0$, $\mathscr{I}m\ k_1 \geq 0$, where $\mathscr{R}e \sqrt{t^2 - k_1^2} \geq 0$. The value of $\sqrt{t^2 - k_1^2}$ at points $t^2 < k_1^2$, $k_1$ real, is determined by continuation of $\sqrt{t^2 - k_1^2}$ from the upper half plane $\mathscr{I}m\ k_1 > 0$. We note that $\mathscr{R}e \sqrt{t^2 - k_1^2}$ cannot change sign, as $k_1$ is varied continuously for fixed $t$, unless $\mathscr{I}m\ k_1$ becomes zero, and that the integral therefore converges, with $\sqrt{t^2 - k_1^2}$ as defined, for $r = 0$ and/or $k_1 = 0$.

Using equation (8), with $(h - z)$ replacing $(h + z)$, so as to represent $\phi_0$, equation (5), we can, as does Sommerfeld, obtain a solution for complex $k_1$. In fact, letting $t = k_1 u$ in equation (8) and the other relevant integrals, the solution in medium 1 is given by equations (5) and (9)–(13), except that the contour for $\phi_t$, equation (11), now runs from 0 to $\infty$ along the line $\arg u = -\arg k_1$. The cuts through $u = 1$ and $u = \alpha$, formerly through $t = k_1$ and $\alpha k_1$, approach infinity along $\arg u = (\pi/2) - \arg k_1$. The cuts through $u = -1$ and $u = -\alpha$, which were downward in the $t$-plane, approach infinity along $\arg u = -(\pi/2) - \arg k_1$. With these provisos, equation (11) can be seen to represent an analytic function of $k_1$ in the entire range $\mathcal{I}m\, k_1 \geq 0$; as always, $k_2 = \alpha k_1$, $\alpha < 1$. This result is most important. Knowing the solutions are analytic functions of $k_1$ enables us, as in the next section, to extend integrals over $\omega$ into the complex $\omega$-plane. If $k_1 = \rho e^{i\theta}$, $0 < \theta < \pi$, the behavior of $\phi_t$, equation (11), for fixed $r$ and $z$ as $\rho \to \infty$ is determined by $\exp\{-\rho(h+z)[\sin\theta\, \mathcal{R}e \sqrt{1-u^2} + \cos\theta\, \mathcal{I}m \sqrt{1-u^2}]\}$. The signs of $\mathcal{R}e \sqrt{1-u^2}$ and $\mathcal{I}m \sqrt{1-u^2}$ are found by analytic continuation of their values in equation (16), as the cuts of Figure 2 are rotated clockwise. It follows that $\sin\theta\, \mathcal{R}e \sqrt{1-u^2} + \cos\theta\, \mathcal{I}m \sqrt{1-u^2}$ is positive for all $u$ on the contour $\arg u = -\arg k_1$, and consequently that equation (11) approaches zero exponentially as $|k_1| \to \infty$, $0 < \arg k_1 < \pi$. Moreover, for $k_1$ real, it can be seen that $\phi_t(-k_1) = [\phi_t(k_1)]$, the bar denoting complex conjugate. This result was of course to be expected since $\phi_0(-k) = \phi_0(k)$ and the differential operator $\Delta^2 + k_1^2$ is real for real $k_1$.

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[9] The plane wave expansion of $e^{ikR}/R$ appears to us to involve divergent integrals in medium 2 whenever $k_2$ is complex even with real $k_1$. When $k_2$ is complex, for any $x$ and $y$, there are values of the azimuth angle $\psi$ in equation (12) of reference 2 for which the integrand becomes infinite as $\theta$ approaches its upper limit of $\pi/2 - i\infty$. This difficulty does not seem to have been remarked by later writers, e.g. Ott.

Using Cauchy's theorem, we may now infer rigorously the result that if $a \geq 0$, $b \geq 0$,

$$\phi_t(-a+ib) = \overline{\phi_t(a+ib)}. \tag{43}$$

We write

$$\phi_t(k_1) = \frac{1}{2\pi i}\int \frac{dK\phi_t(K)}{K-k_1}, \tag{44}$$

the contour being the real axis from $-\infty$ to $\infty$ and then around the circle at infinity in the positive $k_1 \equiv K$-plane. Equation (44) is justified by our demonstration that $\phi_t$ is analytic in the domain, and equation (43) follows at once if we note that the integral over the circle at infinity vanishes since $\phi_t$ has been shown to become zero exponentially on this circle.

The form of the solution so far obtained is awkward. It is more convenient to introduce $2J_0 = H_0^{(1)} + H_0^{(2)}$ as in Section II. This is not possible if $r = 0$ since $H_0^{(1)}(0)$ is not defined. Restricting ourselves to values[10] of $r > 0$, it is then easy to show using $H_0^{(2)}(k_1ru) = -H_0^{(1)}(k_1rue^{i\pi})$ that equation (17) remains valid and is an analytic function of $k_1$, provided the contour $C$ of equation (17) runs from infinity to the origin along the line $\arg u = \pi - \arg k_1$, and then from the origin to infinity along the line $\arg u = -\arg k_1$. The limits within which the contour can be deformed can be inferred from equations (21) and (22), which remain valid, provided $\theta$ is interpreted as $\arg k_1u$ instead of $\arg u$. In $\text{III}_1$ and IV then, the integrand approaches zero exponentially as $u \to \infty$ if

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[10] Obviously, in justifying equation (17) (cf. Section II) we should have stated that $r > 0$ but the fact that our formulas involving $H_0^{(1)}$ are not valid for $r = 0$ is of little moment. It is important however that a valid solution from which the fields at $r = 0$ can be evaluated for any $k_1$ is available (in principle, at any rate), that the analysis for $r > 0$ yields formulas which can be understood and used almost everywhere, and that there is no reason either from the physical properties or from the appearance of the formal solution to expect unusual results on the line $r = 0$.

$(z + h) \cos \theta + r \sin \theta \geq 0$, or it may be deformed from its original $\arg k_1 u = 0$ anywhere within the limits

$$-\tan^{-1} \frac{z+h}{r} \leq \arg k_1 + \arg u \leq \pi - \tan^{-1} \frac{z+h}{r}. \tag{45}$$

In $I_2$ we have from equation (22)

$$\tan^{-1} \frac{z+h}{r} \leq \arg k_1 + \arg u \leq \pi + \tan^{-1} \frac{z+h}{r}. \tag{46}$$

In equations (45) and (46)

$$0 < \tan^{-1} \frac{z+h}{r} < \frac{\pi}{2}.$$

The inequalities hold up to and including the limits; i.e., $\leq$ is correct, if $|k_1| > 0$, as can be seen by substituting the values of $\arg k_1 u$ at the limits in equations (21) and (22). It will be found that $\mathcal{R}e\, A(u)$ is not zero at these values of $\arg k_1 u$, so that equation (17) converges as $\rho \to \infty$.

These results will be used in the following section.

## VII. *Reception of a Pulse*

Suppose the wave radiated by the source at $P$ (Figure 1) is given by

$$\phi_0(t) = \frac{1}{R} f\left(t - \frac{R}{c_1}\right) \tag{47}$$

where $R$ is the distance $PS$ and $f(x) = 0$ for $x < 0$. The function $f(x)$ satisfies sufficient conditions for the existence of a Laplace transform, but is otherwise arbitrary. In particular $f(x)$ satisfies the condition that the integral from 0 to $\infty$ of $|f(x)|$ exists. Then $f(x)$ can be written in the form

$$f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega\, e^{-i\omega x} g(\omega) \tag{48}$$

where $g(\omega)$ is a one-valued regular analytic function of $\omega$ in the entire half plane $\mathcal{I}m\, \omega \geq 0$.

It follows, as is well known, that the solution in medium 1 is given by equation (5) where now

$$\phi_r(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega\, e^{-i\omega t} g(\omega) \phi_r(\omega) \tag{49}$$

with $\phi_r(\omega) \equiv \phi_r$ of eq. (6). The functions $\phi_r(\omega)$ have been derived for all $\mathcal{I}m\, \omega \geq 0$ in the preceding section. In particular $\phi_r(\omega)$ may be replaced by equations (9)–(11). The term $\phi_s(\omega)$ yields a wave which is received at a time $t - d/c_1$ and which duplicates in shape as a function of time the shape of the original wave $\phi_0(t)$. This is also a well known result, and is demonstrated by the usual means of closing the contour in the upper $\omega$-plane. We still have to examine equation

$$\phi_\iota(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\omega\, e^{-i\omega t} g(\omega)\phi_\iota(\omega) \tag{50}$$

which contains all the deviations from geometrical acoustics. From the previous section $\phi_\iota(\omega)$ is known to be a regular analytic function for any $z$, $r$ when $\mathscr{I}m\,\omega \geq 0$. Since $g(\omega)$ is also analytic and regular, the contour may be deformed at will in the region $\mathscr{I}m\,\omega \geq 0$.

Deform the contour so that it makes a small half circle about the origin. This is done to avoid the difficulty $k_1 r = 0$. Assume $r > 0$. Then, in equation (50), $\phi_\iota(\omega)$ is given by equations (17) and (43) with the contour $C(k_1)$ defined as in the previous section, lying within the limits of equations (45) and (46). We shall now show that when $\tau < \alpha$ the integral, equation (50), is zero over the infinite half circle at infinity in the upper $\omega$-plane, $\mathscr{I}m\,\omega \geq 0$, whenever $t - d/c_1 < 0$. Consequently by Cauchy's theorem $\phi_\iota(t) = 0$ whenever $t - d/c_1 < 0$, if $\tau < \alpha$.

We consider first the quarter circle at infinity $0 \leq \arg\omega \leq \pi/2$. For any $k_1$ in this region, $k_1 = \omega/c_1$, $c_1$ real, the contours $C(k_1)$ can be deformed to the contour $C'$ of Figure 3. In order that this deformation be possible, according to equations (45) and (46), it is only necessary that

$$-\tan^{-1}\frac{z+h}{r} \leq \arg k_1 + \tan^{-1}\frac{r}{z+h} \leq \pi - \tan^{-1}\frac{z+h}{r} \tag{51}$$

and

$$\tan^{-1}\frac{z+h}{r} \leq \arg k_1 + \pi - \tan^{-1}\frac{r}{z+h} \leq \pi + \tan^{-1}\frac{z+h}{r}. \tag{52}$$

Equations (51) and (52) are satisfied[11] provided $0 \leq \arg k_1 \leq \pi/2$.

If $C_\rho$ represents the contour along the quarter circle of radius $\rho$, the integral of equation (50), integrated over this contour, can now be written as

$$\begin{aligned} Q(t) = \frac{1}{2\pi}\int_{C_\rho} d\omega\, e^{-i\omega t} g(\omega) \int_{C'} du\, \frac{u}{\sqrt{1-u^2}} \exp\{ik_1(h+z)\sqrt{1-u^2}\} \\ \cdot F(u) H_0^{(1)}\left(\frac{\omega}{c_1} ru\right). \end{aligned} \tag{53}$$

The integral over $C'$ in equation (53) converges uniformly as $u$ approaches infinity for any $\omega$ on $C_\rho$. $C'$ is not a function of $\omega$ and $g(\omega)$ is bounded. It follows that the order of integration can be interchanged for any finite $\rho$, and we need only show that

$$\begin{aligned} \lim_{\rho\to\infty} \frac{1}{2\pi}\int_{C'} du\, \frac{u}{\sqrt{1-u^2}} F(u) \int_{C_\rho} d\omega\, g(\omega) e^{-i\omega t} \\ \cdot \exp\{ik_1(h+z)\sqrt{1-u^2}\} H_0^{(1)}(k_1 ru) = 0. \end{aligned} \tag{54}$$

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[11] They are not satisfied if $\arg k_1 > \pi/2$; this is the reason why a line of reasoning stemming from equation (43) was adopted.

As $\rho \to \infty$, $H_0^{(1)}(k_1ru)$ can be replaced by its asymptotic expansion, for any $u$ on $C'$. $uF(u)/\sqrt{1-u^2}$ is bounded. The limit as $\rho \to \infty$ is therefore determined by the behavior of

$$B(u) = ik_1[A(u) - c_1t] \tag{55}$$

with $A(u)$ defined by equation (19). Letting $k_1 = \rho e^{i\theta}$, it is evident that the limit approaches 0 exponentially as $\rho \to \infty$ provided

$$-\sin\theta\, \mathcal{R}e\, A(u) - \cos\theta\, \mathcal{I}m\, A(u) + c_1t\sin\theta < 0 \tag{56}$$

for all $0 \leq \theta \leq \pi/2$. But however, in Section III the contour $C'$ was so defined that $A(u) = d + i\eta$, where $\eta \geq 0$ for all $u$ on $C'$. Consequently equation (56) is satisfied[12] whenever $-d + c_1t < 0$. On the other hand whenever $-d + c_1t > 0$, there will be a continuous set of values of $u$ on $C'$ for which, for a finite range of angles $\theta$, equation (56) is not satisfied. It follows, using equation (43), that the contour can be closed in the upper half $\omega$-plane whenever $t < d/c_1$, and cannot whenever $t > d/c_1$. In other words $\phi_i(t)$ of equation (49), like the geometrically reflected $\phi_s(t)$, begins at $t = d/c_1$ and not before.

When $\tau > \alpha$ the contour $C(k_1)$ can be deformed into the contours $C_1$ and $C_2$ of Figure 4 and finally into the contours $C_1'$ and $C_2'$ of Figure 5, since the asymptotic limits of $C_1'$ and $C_2'$ are the same as $C'$, so that equations (51) and (52) remain relevant. The integrals continue to be uniformly convergent, and the argument goes just as above. The integral along $C_2'$ leads to the same conclusion, namely that the signal is received when $t = d/c_1$. The integral along $C_1'$ leads to equation (56) where in this case $\mathcal{R}e\, A(u) = r\alpha + (z+h)\sqrt{1-\alpha^2}$, so that along this path the signal is received only when

$$t = \frac{r\alpha + (z+h)\sqrt{1-\alpha^2}}{c_1} = \frac{PA + SB}{c_1} + \frac{AB}{c_2} \qquad \text{(Figure 1).}$$

That no poles are crossed deforming the contours when $\tau < \alpha$, and that the pole is crossed when $\tau > \alpha$ only when $\alpha < \beta < 1$ and equation (30) is satisfied is shown just as in Sections III and IV. When $\phi_i(p)$ contributes, $K_0$ is replaced by its asymptotic expansion in equation (28) and it is found that $\phi_i(p)$ does not contribute until $c_1t$ equals $(z+h)(1-\alpha^2)^{1/2}/(1-\beta^2)^{1/2}$. That this time lies between the times of appearance of the head wave and the directly reflected wave follows from equation (30). Because this time involves $\beta$, no simple geometrical interpretation of $\phi_i(p)$ is possible.

## BIBLIOGRAPHY

[1] G. Joos and J. Tetlow, *Propagation of explosive waves at the surface of separation of two media*, Physikalische Zeitschrift, Volume 40, 1939, pp. 289–293.

[2] E. Gerjuoy, *Refraction of waves from a point source into a medium of higher velocity*, Physical Reviews, Volume 73, 1948, pp. 1442–1449.

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[12] The isolated point $u = \tau$, $\theta = 0$ at which the left side of equation (56) equals zero for all values of $t$ can be shown to give no finite contribution to the integral of equation (54).

[3] H. Jeffreys, *Compressional waves in two superposed layers*, Cambridge Philosophical Society Proceedings, Volume 23, 1926, pp. 472–481.

H. Lamb, *Propagation of tremors over the surface of an elastic solid*, Philosophical Transactions of the Royal Society, Series A, Volume 203, 1904, pp. 1–42.

M. Muskat, *Theory of refraction shooting*, Physics (now Journal of Applied Physics), Volume 4, 1933, pp. 14–28.

H. Ott, *Reflection and refraction of spherical waves*: Effects of the second order, Annalen der Physik, Volume 41, 1942, pp. 443–446.

M. Kruger, *Die Theorie der in endlicher Entfernung von der Trennungsebene zweier Medien erregten Kugelwelle für endliche Brechungsindizes*, Zeitschrift für Physik, Volume 121, 1943, pp. 377–477.

[4] L. Brehovskih, *Reflection of spherical waves on the plane separation of two media*, Journal of Technical Physics, USSR, Volume 18, 1948, pp. 455–472.

[5] J. A. Stratton, *Electromagnetic Theory*, McGraw-Hill, New York, 1941, p. 576.

[6] G. N. Watson, *Treatise on the Theory of Bessel Functions*, Macmillan, New York, 1944, p. 416.

[7] H. Weyl, *Radiation of electric waves over a plane conductor*, Annalen der Physik, Volume 60, 1919, pp. 481–500.

[8] A. Sommerfeld, *Über die Ausbreitung der Wellen in der drahtlosen Telegraphie*, Annalen der Physik, Volume 28, 1909, pp. 665–736.

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# Geographic and Systematic Status of the Fishes Described by Kner and Steindachner in 1863 and 1865 from Fresh Waters in Panamá and Ecuador[1]

Carl L. Hubbs

IN this paper I attempt to clarify the localities and the identifications of the fishes that Kner and Steindachner described in 1863 and 1865 from fresh waters in Panamá and Ecuador, on the basis of the pioneering collections of zoogeographer Moritz Wagner.

Chief reference has been made to their main report, the date of which is ordinarily given as 1864, but is listed in Dean's *Bibliography of Fishes* (1, 1916: 694) as 1870. It is here assumed to be 1865, in accordance with the remark by Günther (1866: 173), "although this memoir is dated 1864, its publication appears to have been delayed to 1865, and it could not be obtained through booksellers before 1866."

As Günther noted, the new species differentiated by Kner and Steindachner (18, not 17) were first characterized in the Sitzungsberichte of the Bavarian Academy for 1863. That paper is not listed in Dean's *Bibliography of Fishes* and has apparently seldom been consulted. This preliminary contribution was presented by von Siebold but is definitely accredited to Rudolf Kner. The species should be attributed to Kner and Steindachner, however, for Kner stated (p. 221):

> Hoch erfreut und geschmeichelt durch diese ehrenvolle Aufforderung, unternahm ich in Vereine mit meinen jungen Freunde F. Steindachner, Adjunkten am Kais. Hof-Naturalienkabinete die Lösung dieser Aufgabe.

The original diagnoses are acceptably given in Latin, with comparative notes in German.

As Günther also noted, the main report by Kner and Steindachner was followed by a geographical and ecological treatise, by Wagner

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 610.

(1865), based on the same collection. It would appear that this report also has been little used.

One source of confusion regarding localities has stemmed from Kner and Steindachner's use of "Neu-Granada." In their time Nueva Granada was equivalent to Colombia and included Panamá (earlier the viceroyalty of Nueva Granada covered northwestern South America, including Venezuela and Ecuador as well). That all of Kner and Stendachner's "Neu-Granada" localities are ascribable to Panamá was made clear by Wagner (1865: 90, footnote 1) in the following generally overlooked statement:

> Nach diesen genaueren Angaben des Vorkommens sind einige kleine Irrthümer, die sich in die vorhergehende Abhandlung der Herren Kner und Steindachner hinsichtlich der Fundorte eingeschlichen haben, zu berichtigen. Wo dort "Neu-Granada" als Fundort genannt wird, ist immer der Isthmusstaat Panama gemeint, der zum Gebiet der Republik Neu-Granada gehört.

The species treated by Kner and Steindachner may now be considered in systematic order.

### SQUALIDAE

#### ?*Squalus cubensis* Howell Rivero, 1936

*Acanthias vulgaris*, Risso?—Kner and Steindachner (in Kner, 1863: 230), "Panama, Nordseite."—This record has obviously been the basis for the inclusion of "Panama" in the range of species of *Squalus* (= *Acanthias*). It was entered by Günther (1868: 396) in his distributional table, where the species *Acanthias vulgaris* is listed as marine from "*Atl., Ind., & Pac. Oceans* (Panama)." Wagner (1865: 90) wrote that he took the species in brackish water in stream mouths on both sides of the Isthmus. Kner and Steindachner, however, listed only one specimen and specified "Nordzeite." Since Wagner was rather careless in his listings, the record from the Pacific may be regarded as erroneous and we may doubt that the "Nordseite" specimen came from brackish water. We may, therefore, disregard the Pacific Panamá records of "*Squalus sucklii* (Girard)," by Gilbert and Starks (1904: 13) and of *Squalus* (species not identified), by Meek and Hildebrand (1923: 64–65). It seems probable, however, that Wagner did collect a *Squalus* on the Atlantic side of Panamá. It may well have been a specimen of *Squalus cubensis* Howell Rivero, which is known definitely from Cuba and probably from Trinidad and Brazil (Bigelow and Schroeder, 1948: 473–78).

### ENGRAULIDAE

#### *Lycengraulis poeyi* (Kner and Steindachner, 1863)

*Engraulis Poeyi*, n.—Kner and Steindachner (in Kner, 1863: 224; 1865; 23–24, pl. 3, fig. 3), "Rio Bayano, Panama."—The original diagnosis of this species has consistently been overlooked.

#### *Anchovia macrolepidota* (Kner and Steindachner, 1863)

*Engraulis macrolepidota*, n.—Kner and Steindachner (in Kner, 1863: 224; 1865: 21–23, pl. 3, fig. 2), "Rio Bayano, Panama."—The original diagnosis of this well-known species, also, has consistently been overlooked.

### CHARACIDAE

#### *Saccodon wagneri* Kner and Steindachner, 1863

*Saccodon Wagneri*, n.—Kner and Steindachner (in Kner, 1863: 225; 1865: 31–35, pl. 4, fig. 2), "aus dem Staate Ecuador" (1863); "Ecuador" (1865).—The original diagnosis of this endemic characin has been overlooked, as by Eigenmann (1922: 112), though the standard nomenclators refer to the 1863 naming of the genus. Wagner (1865: 34) indicated that the species lives in the middle region of the streams on the west side of the Andes, between 1,000 and 6,000 feet elevation.

#### *Brycon atricaudatus* (Kner and Steindachner, 1863)

*Chalceus atricaudatus*, n.—Kner and Steindachner (in Kner, 1863: 227; 1865: 44–47, pl. 4, fig. 3), "von Westabhange der Andes im Staate Ecuador."—This species has wrongly been accredited, as by Eigenmann (1922: 131) to Kner alone.

#### *Brycon striatulus* (Kner and Steindachner, 1863)

*Chalcinopsis striatulus*, n.—Kner and Steindachner (in Kner, 1863: 226; 1865: 38–41, pl.

5, fig. 2), "Panama" (1863); "Neu-Granada [properly, Panamá] und Panama an der Seite des stillen Ocean" (1865).—For some reason this species and the next have also consistently been attributed to Kner alone. These two forms were long synonymized, but have been treated as distinct in more recent reviews (Meek and Hildebrand, 1916: 293–99; Eigenmann, 1922: 129–39; Hildebrand, 1938: 274–86). Perhaps having both species in mind, Wagner (1865: 90) stated that *Chalcinopsis striatulus* occurs in the middle section of the streams on both watersheds.

### *Brycon chagrensis* (Kner and Steindachner, 1863)

*Chalcinopsis chagrensis*, n.—Kner and Steindachner (in Kner, 1863: 226; 1865: 42–43, pl. 5, fig. 3), "Rio Chagres an der Nordseite von Panama."—This species has passed through the same nomenclatorial history as the last. The specific name in their synonymic reference was misspelled *chagresensis* by Jordan and Evermann (1896: 337).

### *Pseudochalceus lineatus* Kner and Steindachner, 1863

*Pseudochalceus lineatus*, n.—Kner and Steindachner (in Kner, 1863: 225–26; 1865: 35–38, pl. 5, fig. 1), "vom Westabhange der Anden im Staate Ecuador."—This species has been accredited wrongly to Kner alone, as by Eigenmann (1921: 227; 1922: 140), who, furthermore, wrongly quoted Wagner as stating that it occurs only at about 1,000 feet elevation. Wagner wrote that it lives on the western slope of the Andes at elevations between 1,000 and 6,000 feet.

### *Astyanax* sp.

*Tetragonopterus aeneus* Günth.—Kner and Steindachner (in Kner, 1863: 229; 1865: 46), "Rio Chagres."—*Tetragonopterus Gronovii* C. V.—Kner and Steindachner (in Kner, 1863: 229; 1865: 46–47), "Rio Bayano."—Since the species of *Astyanax* in Panamá are distinguished chiefly by color (Meek and Hildebrand, 1916: 280–82; Eigenmann, 1921: 227–310; 1922: 142–45; Eigenmann and Myers, 1929: 541–42; Hildebrand, 1938: 257–64), and are still of uncertain status, and since Kner and Steindachner described their material very briefly, with no color notes, I venture no specific identification of their specimens, allegedly of two species. Wagner (1865: 90), carelessly, I presume, attributed both species to both watersheds.

### *Hoplias microlepis* (Günther, 1860)

*Macrodon (Erythrinus) brasiliensis* (Spix) or *Macrodon fasciatus* ("ist fraglich, vielleicht doch neue Art und dann also Macrod. fasciatus zu bezeichnen").—Kner and Steindachner (in Kner, 1863: 229), "aus Neu-Granada und dem Rio Chagres."—This case poses a nomenclatorial problem. In the 1863 account there is no trace of description, merely the name, locality, specimen numbers, and the statement quoted above regarding the new designation to be applied if, possibly, the form should be distinct. In the 1865 account, under the heading "Gattung: **Macrodon**, J. Müll.," Kner and Steindachner discussed the characters of the Panamá specimens and compared them with accounts of several species, but did not arrive at a specific identification. In this discussion they made no reference to the name *fasciatus*. Nor, so far as apparent, has any other ichthyologist taken cognizance of this name, which, presumably, can be regarded as a *nomen nudum*. If, on the basis of the expanded treatment of 1865, it should be thought that the name is available, the case should be submitted to the International Commission on Zoological Nomenclature for such action as might be needed to suppress the name. I select "Chagres River" as the type locality of *Macrodon microlepis* Günther (1864: 282) and thus make it the precise equivalent of *Macrodon fasciatus*. Günther, by slip, gave the range of *microlepis* as "Western Ecuador; Guatemala," for he listed specimens only from "Western Ecuador" and "Chagres River." The latter were extant in 1908, when they were included by Regan (1908: 167) as "the types of the species" in his redescription of *Hoplias microlepis*. The status of the form was discussed by Meek and Hildebrand (1916: 303–05), Eigenmann (1922: 169–70), and Hildebrand (1938: 289–90). Wagner (1865: 90) listed "*Macrodon brasiliensis?* Spix" from both watersheds of the Isthmus.

### GYMNOTIDAE

### *Sternopygus macrurus* (Bloch and Schneider, 1801)

*Sternopygus macrourus* Mll. Tr.—Kner and Steindachner (in Kner, 1863: 230), "Rio Guajaquil in Ecuador."—This locality for the wide-ranging species was verified by Eigenmann (1922: 172–73).

### ARIIDAE

### *Arius multiradiatus* Günther, 1864

*Bagrus ? arioides*, n.—Kner and Steindachner (in Kner, 1863: 227; 1865: 47–49), "Rio Bayano im Staate Panama, Südseite."—On the synonymy of this species, consult Meek and Hildebrand (1925: 123).

### PIMELODIDAE

### *Rhamdia wagneri* (Günther, 1868)

*Pimelodus cinerascens* Günth.—Kner and Steindachner (in Kner, 1863: 229; 1865: 49–52), "Neu-Granada" (1863); "Rio Chagres, Guajaquil [see next species] und Neu-Granada [properly, Panamá]" (1865).—Meek and Hildebrand (1916: 240) referred the Panamá records to *R. wagneri*. Wagner (1865: 90) reported "*Pimelodus cinerascens*" from both watersheds of the Isthmus.

### *Rhamdia cinerascens* Günther, 1860

*Pimelodus cinerascens* Günth.—Kner and Steindachner (in Kner, 1863: 229; 1865: 52), "Guajaquil" material only.—Since *cinerascens* was described by Günther (1860: 237, pl. 10, fig. A) from "fresh waters of Guayaquil and Esmeraldas," and since I here designate Guayaquil as the type locality, the "Guajaquil" record by Kner and Steindachner may be regarded as correctly identified.

### ? *Pimelodella chagresi* (Steindachner, 1876)

*Pimelodus modestus* Günth.—Kner and Steindachner (in Kner, 1863: 229; 1865: 49), "Rio Chagres."—Regan (1907: 137) has suggested that this record of *modestus*, unaccompanied by a description, was not improbably based on *P. chagresi*.

### ASTROBLEPIDAE

### *Astroblepus grixalvii* von Humboldt

*Brontes prenadilla* C. V.—Kner and Steindachner (in Kner, 1863: 230), "Cotopaxi."—This specimen was a topotype of *Brontes prenadilla* Valenciennes, which Eigenmann (1922: 53) synonymized with *Astroblepus grixalvii* von Humboldt.

### TRICHOMYCTERIDAE

### *Trichomycterus laticeps* Kner and Steindachner, 1863

*Trichomycterus laticeps*, n.—Kner and Steindachner (in Kner, 1863: 228; 1865: 54–56, pl. 6, fig. 2), "Fundort, wie die vorige Art [*T. taenia*]."—This form has wrongly been accredited to Kner alone, as by Eigenmann (1918: 307; 1922: 60).

Tchernavin (1944: 244–45), taking violent issue with Eigenmann and Eigenmann (1890: 325; quoted by Eigenmann, 1909: 247–48), gave seemingly valid reasons for rejecting the name *Pygidium* for this genus and entered a strong plea for returning to *Trichomycterus*. The name "*thrichomycterus*" as proposed by von Humboldt (quoted by Eigenmann, 1918: 341) may be interpreted as a vernacular and, therefore, as having no standing. *Trichomycterus* Valenciennes would then surely be valid. Under the complicated circumstances, however, it may require a special decision of the International Commission on Zoological Nomenclature to restore validly the name *Trichomycterus*.

### *Trichomycterus taenia* Kner and Steindachner, 1863

*Trichomycterus taenia*, n.—Kner and Steindachner (in Kner, 1863: 228; 1865: 52–54, pl. 6, fig. 1), "vom Westabhange der Andes im Staate Ecuador."—This is another species that has been accredited to Kner alone, as by Eigenmann (1918: 310; 1922: 61). Since Kner and Steindachner used the form *taenia* in conjunction with a genus of masculine gender it is obvious that they employed a noun, which is not to be declined (as Eigenmann did in the combination *Pygidium taenium*).

### LORICARIIDAE

### *Plecostomus plecostomus panamensis* Eigenmann, 1922

*Hypostomus plecostomus?* C. V.—Kner and Steindachner (in Kner, 1863: 230; 1865: 60–61), "Neu-Granada [properly, Panamá]."—

Eigenmann (1922: 69) referred Kner and Steindachner's account to the synonymy of iis new subspecies, *panamensis*.

### *Ancistrus chagresi* Eigenmann and Eigenmann, 1889

*Ancistrus* (*Hypostomus*) *cirrhosus* Kn.—Kner and Steindachner (in Kner, 1863: 229; 1865: 60–61), "Rio Chagres."—Meek and Hildebrand (1916: 251) referred Kner and Steindachner's account to the synonymy of *A. chagresi*.

### *Loricaria uracantha* Kner and Steindachner, 1863

*Loricaria uracantha*, n.—Kner and Steindachner (in Kner, 1863: 228–29; 1865: 56–58, pl. 6, fig. 3), "aus dem Rio Chagres, Nordseite von Panama" (1863); "aus Neu-Granada [properly, Panamá] und dem Rio Chagres" (1865).—Apparently on the basis of Wagner's (1865: 90) probably careless and incorrect statement, Günther (1868: 393, 478), Eigenmann (1910: 413), and others reported this species on both slopes of the Isthmus. As the result of their surveys Meek and Hildebrand (1916: 257) and Hildebrand (1938: 241) doubted the Pacific drainage reports.

A second species "aus dem Rio Chagres" was identified by Kner and Steindachner (1863: 229; 1865: 58–60) with *Loricaria lima* Kner, 1853. Wagner (1865: 90) and Günther (1868: 393) attributed it also to both watersheds of the Isthmus, likely in error. Eigenmann and Eigenmann (1891: 39) and Jordan and Evermann (1896: 158) accepted the Panamá record, but Meek and Hildebrand ignored it. Regan (1907: 113) referred Kner and Steindachner's *L. lima* to *L. uracantha*.

## POECILIIDAE

### *Mollienisia sphenops gilli* (Kner and Steindachner, 1863)

*Xiphophorus Gillii.*—Kner and Steindachner (in Kner, 1863: 224; 1865: 25–28, pl. 4, fig. 1), "Rio Chagres."—The original and adequate diagnosis of this form has been missed by subsequent authors.

The name *gilli* is certainly applicable to a Panamá subspecies of *M. sphenops*. It is the oldest name available for any subspecies from south of México. The type locality may be designated as the middle reaches of Río Chagres. This river is the only one mentioned by Kner and Steindachner in either paper, though Wagner (1865: 90) attributed the species to both watersheds of the Isthmus. Wagner included it among those he had collected "in süssen Wasser des mittleren Flusslaufes."

The distinctiveness of the middle-Chagres form of *M. sphenops* is indicated by an examination of numerous specimens from the river itself and from the large reservoir (Lake Chagres) in its course. The genetic validity of the characters has been confirmed by extensive breeding experiments in which this subspecies was utilized along with several others. *M. s. gilli* may be distinguished by the following characterization. The size is generally small to moderate and males often mature when very small. Higher males have the body and caudal peduncle moderately deep and the dorsal fin often greatly elongated, at times considerably overlapping the basal part of the caudal fin. The dorsal base, however, is short, for the fin has 7 to 10, usually 9 rays, counting all elements, the last pair as one (in several topotypic series I have counted 7 dorsal rays in 1 specimen, 8 in 44, 9 in 114, 10 in 1). In young females and in low males the basal part of the dorsal is more or less blackened. Males have rather faint vertical bars and both males and females have rows of faint spots. The gonopodium usually retains, more or less well developed, the membranous hook at the tip of ray 3, but the retrorse segment at the tip of ray 5p is variably weakened. There is no mustache. The teeth of the inner bands of the jaws are strictly unicuspid. These bands are unusually narrow (only 2 to 4 teeth wide), slightly curved medially, incurved toward the rather wide median separation. Each premaxillary band is sharply recurved backward and inward from its outer end. There is almost no backward projection from the outer end of the mandibular band. The lower margin of the preorbital, which turns upward just behind the lowest preorbital pore, is usually more or less completely bound down by a thin, easily ruptured membrane, and one or more of the 3 preorbital pores are commonly covered by membrane.

### ?*Agonostomus monticola* (Bancroft, 1836)

*Dajaus elongatus*, n.—Kner and Steindachner (in Kner, 1863: 222; 1865: 6–9, pl. 1, fig. 2), "Panama" (1863) or "Neu-Granada [properly, Panamá]" (1865).—This nominal species was, oddly, overlooked by Jordan and Evermann (1896: 819–20), Regan (1907: 66–69), Meek and Hildebrand (1916: 333–36), and Hildebrand (1938: 322–24), although it was treated by Günther (1866: 192; 1868: 444–45) as a synonym of his own *Agonostoma nasutum*. On the basis of the revision by Regan one might concur with Günther's identification, but the genus *Agonostomus* is in great need of revision. Meek and Hildebrand (1916: 334–35) regarded *A. nasutus* as a synonym of *A. monticola*, placing no reliance on the thickness or shape of the lip. Pending further study, I accept their judgment.

Kner and Steindachner (in Kner, 1863: 229; 1865: 8–9) separated two other species, *Dajaus monticola* from "Neu-Granada" (properly, Panamá) and *D. nasutus* ("von der Westküste Panamas"). Of the authors quoted in the last paragraph only Günther took cognizance of these records. He referred Kner and Steindachner's *D. nasutus* to *Agonostoma nasutum*, but accepted the specific identification of their *D. monticola*. Their *D. monticola*, however, would probably also be *Agonostomus nasutus*, if valid, because they describe their "Neu-Granada" specimen as having the snout blunter and more convex toward the tip than in the two other species.

Wagner (1865: 89–90) indicated, perhaps loosely, that he had caught all three nominal species in the brackish water of stream mouths on both sides of the Isthmus.

## HAEMULIDAE

### *Pomadasys bayanus* Jordan and Evermann, 1898

*Pristipoma humile*, n.—Kner and Steindachner (in Kner, 1863: 221–22; 1865: 3–5, pl. 1, fig. 1), "Rio Bayano, Staat Panama, Südseite."—Jordan and Evermann (1898: 1331) replaced Kner and Steindachner's preoccupied name with *Pomadasis bayanus*. As Meek and Hildebrand (1925) indicated, the original as well as the classically correct spelling of the generic name is *Pomadasys*.

## CICHLIDAE

### *Aequidens coeruleopunctatus* (Kner and Steindachner, 1863)

*Acara coeruleopunctata*, n.—Kner and Steindachner (in Kner, 1863: 222–23; 1865: 16–18, pl. 2, fig. 3), "Rio Chagres im Staate Panama, Nordseite" (1863); "aus dem Rio Chagres und von westlichen Gehänge der Andes" (1865).—This species has been correctly cited, except in that Jordan and Evermann (1898: 1514) accredited Salvin as the collector of the types. Wagner (1865: 90) indicated that he had taken the species in the middle course of streams on both watersheds of the Isthmus, possibly referring to the record from the western slope of the Andes. Eigenmann (1922: 197), however, doubted the occurrence of this cichlid in northwestern Ecuador.

### *Cichlasoma altifrons* (Kner and Steindachner, 1863)

*Heros altifrons*, n.—Kner and Steindachner (in Kner, 1863: 223; 1865: 11–13, pl. 2, fig. 1), "Panama" (1863); "Neu-Granada [properly, Panamá]" (1865).—This species was omitted by Meek and Hildebrand (1916), because, according to Hildebrand (1938: 328–29), "of the uncertainty regarding the type locality." This doubt might have been dispelled had they checked the original description, and certainly would have been eliminated, had they read Wagner's (1865: 90) statement that this "ausgezeichnete Art findet sich weder im Rio Bayano, noch im Rio Grande der Südseite, sondern ausschliesslich nur in den südlichen Flüssen des Department Chiriqui (West-Veragua)." Günther (1868: 391, 459) and Eigenmann (1910: 475) repeated this type locality, which has been verified by Behre (1928: 321). We may now negate the statement (Jordan and Evermann, 1898: 1538) that *altifrons* ranges southward beyond the Isthmus of Panamá and deny the allocation of the species to Colombia (in modern limits) by Regan (1905: 243; 1906: 25) and by Hildebrand (1938: 329). It was not attributed to that country by Eigenmann (1922: 203–04). Since *C. altifrons* appears to occupy the adjacent parts of the Pacific drainage of Panamá and Costa Rica, there is no reason to accept Hildebrand's characterization of its range as peculiar.

### *Paraneetroplus sieboldi* (Kner and Steindachner, 1863)

*Heros Sieboldii*, n.—Kner and Steindachner (in Kner, 1863: 223; 1865: 13–15, pl. 2, fig. 2), "Panama an der Südseeseite" (1863); "Neu-Granada [properly, Panamá] und vom westlichen Abhange der Panama-Landenge" (1865).—Meek and Hildebrand (1916: 346) and Hildebrand (1938: 336–37) commented on their failure to find this species in Panamá and again confounded "Neu-Granada" with Colombia in the modern sense. This species was attributed to Colombia also by Regan (1905: 235; 1906: 30), and by Eigenmann (1910: 474) once, though he properly excluded it from his 1922 monograph on the fishes of northwestern South America. It probably has a distribution like that of *Cichlasoma altifrons*, on the Pacific slope in the Chiriqui province of Panamá and in Costa Rica. In this regard I agree provisionally with the synonymies of Regan (1908: 186) and Hildebrand (1938: 336) and disagree with those of Meek (1914: 127) and of Behre (1928: 323–24). Wagner may well have taken this species, along with *C. altifrons*, only on the Pacific side of Chiriqui province, though he stated (1865: 90) that he took it in the middle course of the streams of both drainages of Panamá.

## ELEOTRIDAE

### *Eleotris picta* Kner and Steindachner, 1863

*Eleotris picta?* n.—Kner and Steindachner (in Kner, 1863: 223–24; 1865: 18–21, pl. 3, fig. 1—misspelled *pictus* in 1865 text, but not on plate), "Rio Bayano, Südseite von Panama" (1863); "Neu-Granada [properly, Panamá] und aus dem Rio Bayano" (1865).—The original (1863) diagnosis of this species has been overlooked. Its synonymy and distribution have been treated in a separate paper (Hubbs, 1953).

## LITERATURE CITED

BEHRE, ELLINOR H. 1928. A list of the fresh water fishes of western Panama between Long. 81° 45′ and 83° 15′ W. *Ann. Carnegie Mus., 18: 305–28, 18–19.*

BIGELOW, HENRY B., AND WILLIAM C. SCHROEDER. 1948. Fishes of the western North Atlantic. Part One. Sharks. *Mem. Sears Found. Mar. Res., 1 59–546, figs. 6–106.*

CUVIER [GEORGES] AND A. VALENCIENNES. 1846. Histoire Naturelle des Poissons, *18: i-xix, 1–505, pls. 520–53.*

DEAN, BASHFORD. 1916. A bibliography of fishes. Enlarged and edited by Charles Rochester Eastman. *Vol. 1: i–xii, 1–718.*

EIGENMANN, CARL H. 1909. The fresh water fishes of Patagonia and an examination of the Archiplata–Archhelenis theory. *Repts. Princeton Univ. Expeds. Patagonia, 1896–1899, 3: 295–374, 34 maps, pls. 30–37.*

——— 1910. Catalogue and bibliography of the fresh water fishes of the Americas south of the Tropic of Cancer. *Ibid.: 375–511.*

——— 1918. The Pygidiidae, a family of South American catfishes. *Mem. Carnegie Mus., 7: 259–398, figs. 1–39, pls. 36–56.*

——— 1921. The American Characidae [part 3]. *Mem. Mus. Comp. Zool. Harvard Coll., 43 (3): 209–310, pls. 30–92.*

——— 1922. The fishes of western South America, part I. The fresh-water fishes of northwestern South America, including Colombia, Panama, and the Pacific slopes of Ecuador and Peru, together with an appendix on the fishes of the Rio Meta in Colombia. *Mem. Carnegie Mus., 9: 1–346, figs. 1–21, pls. 1–38.*

——— AND ROSA SMITH EIGENMANN. 1890. A revision of the South American Nematognathi or cat-fishes. *Occ. Pap. Calif. Acad. Sci., 1: 1–509, figs. 1–57, 1 map.*

——— ——— 1891. A catalogue of the freshwater fishes of South America. *Proc. U. S. Nat. Mus., 14: 1–81.*

——— AND GEORGE S. MYERS. 1929. The American Characidae [part 5]. *Mem. Mus. Comp. Zool. Harvard Coll., 43 (5): 429–558, pls. 57–94.*

GILBERT, CHARLES H., AND EDWIN C. STARKS. 1904. The fishes of Panama Bay. *Mem. Calif. Acad. Sci., 4: 3–304, pls. 1–33.*

GÜNTHER, ALBERT. 1860. Third list of cold-blooded Vertebrata collected by Mr. Fraser in Ecuador. *Proc. Zool. Soc. London, 1860 (28): 233–40, pl. 10.*

——— 1864. Catalogue of the Physostomi, containing the families Siluridae, Characinidae, Haplochitonidae, Sternoptychidae, Scopelidae, Stomiatidae, in the collection of the British Museum. *Cat. Fishes Brit. Mus., 5: i–xxii, 1–455, sev. figs.*

——— 1866. Pisces. *The Record of Zoological Literature, 2 (1865): 163–210.*

——— 1868. An account of the fishes of Central America, based on collections made by Capt. J. M. Dow, F. Godman, Esq., and O. Salvin, Esq. *Trans. Zool. Soc. London, 6: 377–494, pls. 63–87.*

HILDEBRAND, SAMUEL F. 1938. A new catalogue of the fresh-water fishes of Panama. *Publ. Field Mus. Nat. Hist., Zool. Ser., 22: 217–359, 13 figs.*

HUBBS, CARL L. 1953. *Eleotris picta* added to the fish fauna of California. *Calif. Fish and Game, 39 (1): 69–76, figs. 1–2.*

JORDAN, DAVID STARR, AND BARTON WARREN EVERMANN. 1896. The fishes of North and Middle America.... Part I. *Bull. U. S. Nat. Mus., 47 (1): i–lx, 1–1240.*

——— ——— 1898. The same. Part II. *Ibid., 47 (2): i–xxx, 1241–2183, 2 figs.*

KNER, RUD. 1863. Eine Uebersicht der ichthyologischen Ausbeute des Herrn Professors Dr. Mor. Wagner in Central-Amerika, *Sitzungsber. Akad. Wissensch. München, 1863, vol. 2: 220–30* (attributed in text to Kner and Steindachner).

——— AND FRANZ STEINDACHNER. "1864" (1865). Neue Gattungen und Arten von Fischen aus Central-Amerika; gesammelt von Prof. Moritz Wagner. *Abh. Akad. Wissensch. München, 10 (1): 1–61, pls. 1–6.*

MEEK, SETH EUGENE. 1914. An annotated list of the fishes known to occur in the fresh waters of Costa Rica. *Publ. Field Mus. Nat. Hist.*, (*Zool. Ser.*) *10: 101–34.*

——— AND SAMUEL F. HILDEBRAND. 1916. The fishes of the fresh waters of Panama. *Ibid.: 217–374, figs. 1–10, pls. 6–32.*

——— ——— 1923. The marine fishes of Panama. Part I. *Ibid., 15 (1): i–xi, 1–330, pls. 1–24.*

——— ——— 1925. The same. Part II. *Ibid., 15 (2): xv–xix, 331–707, pls. 25–71.*

MÜLLER [JOHANNES]. 1844. Einige Bemerkungen über die auch nach Valenciennes trefflicher Arbeit in v. Humboldt recueil etc. noch immer unvollständig gekannte Familie der Cyprinodonten. *Ber. Akad. Wissensch. Berlin, 1844: 35–36.*

REGAN, C. TATE. 1905. A revision of the fishes of the American cichlid genus Cichlasoma and of the allied genera (continued). *Ann. and Mag. Nat. Hist.*, (*7*) *16: 225–43.*

——— 1906–1908. Pisces. *Biologia Centrali-Americana: i–xxxiii, 1–203, 26 pls., 7 maps, 1 fig.*

STEINDACHNER, FRANZ. 1863. Beitrage zur Kenntniss der Sciaenoiden Brasiliens und der Cyprinodonten Mejicos. *Stizungsber. Akad. Wissensch. Wien, 48: 162–85, pls. 1–4.*

TCHERNAVIN, V. V. 1944. A revision of some Trichomycterinae based on material preserved in the British Museum (Natural History). *Proc. Zool. Soc. London, 114: 234–75.*

TROSCHEL [F. H.]. 1845. Bericht über die Leistungen in Gebiete der Ichthologie während der Jahr 1844. *Arch. Naturgesch., 1845: 200.*

WAGNER, MORITZ. "1864" (1865). Ueber die hydrographischen Verhältnisse und das Vorkommen der Süsswasserfische in den Staaten Panama und Ecuador. Ein Beitrag zur Zoogeographie Amerika's. *Abh. Akad. Wissensch. München, 10* (*1*)*: 63–113.*

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# The Detection of Weak Signals by Correlation Methods*

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(Received July 3, 1952)

A procedure involving autocorrelation is described which, for long averaging time and incoming signals with continuous spectrum, has a detection threshold equal to that of a corresponding conventional system consisting of band pass filter, rectifier, and low pass filter. The autocorrelation procedure is quite complex; a full autocorrelation function is computed and then subjected to a "filtering" operation. A simpler procedure, such as computing autocorrelation coefficients for only one or a few delay times, will in general be less effective. A third process, involving multiplication by a local sinusoidal signal, is also discussed and shown to be closely parallel to the conventional system.

A REPORT with the above title has been issued and given limited distribution.[1] To make the main conclusions more generally available, the following condensation is given here.

The general problem considered is that of recognizing the presence of a small steady signal within a fixed time $T$ after it has been added to a steady background noise n any communication channel. The familiar way of doing this is with a filter and rectifier (see discussion of Fig. 1, below). Autocorrelation and cross correlation have recently received a good deal of attention as alternative procedures.[2,3] The sensitivities of correlation processes have been studied analytically.[4–7] The particular schemes discussed here are chosen to show close parallelism with the familiar filter-rectifier method. The detection thresholds found for these analogous methods are generally alike or comparable, as may be expected.

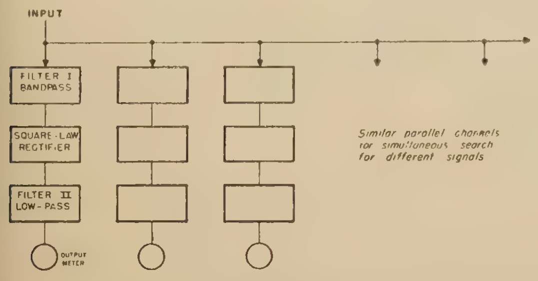

FIG. 1. Filter-rectifier system.

Figures 1, 2, and 3 are block diagrams of three detection processes. The output of each is the continuous indication of a meter whose mean or dc reading changes with presence or absence of the signal. The meter must of necessity also show fluctuations due to background which establish a lower limit to the magnitude of signal which can be detected. To make this threshold determinate it is essential to specify some time interval $T$ within which the signal must be detected. This sets an upper limit on the transient response time of the detection system, and a lower limit on the background frequencies which can be eliminated in the output.

Figure 1 represents a conventional process. Filter I introduces a favorable spectral selectivity. The rectifier generates a dc component which measures input power and can indicate presence or absence of signal. Filter II is low pass, transmitting the dc component while rejecting as much fluctuation as possible, consistent with the requirement or transient time of the system. If the spectral character of the signal is not known in advance, a set of parallel channels may in principle be added, with filters I differing in center frequency, band width, etc.

The system shown in Fig. 2 is, in brief, a set of correlators which jointly compute the full autocorrelation function of the input. These are followed by one or more analyzing networks which respond to components of particular form in this autocorrelation function. Each correlator channel receives two versions of the input differing by a relative time delay $\tau$ which is fixed for any one channel but varies from one to another channel. A multiplier forms the product of the displaced inputs which is then averaged by a low pass filter II. The set of dc outputs of the various channels presents the mean displaced product, or by definition the autocorrelation, of the input as a function of $\tau$. Each analyzing network forms an instantaneous linear combination of all these outputs, the set of coefficients in

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* This work represents one of the results of research carried out under contract with the Bureau of Ships, Navy Department. Contribution No. 611 from the Scripps Institution of Oceanogaphy.

[1] Philip Rudnick, "The detection of weak signals by correlation methods," Marine Physical Laboratory of the Scripps Institution f Oceanography, La Jolla, California, SIO Ref. 52–26, May 10, 952. Additional copies, as long as available, may be had upon equest.

[2] Lee, Cheatham, and Wiesner, Proc. Inst. Radio Engrs. 38, 1165 1950).

[3] F. W. Hunt, Proc. Inst. Radio Engrs. 39, 840 (1951).

[4] Carl Eckart, "The measurement and detection of steady A.C. and D.C. signals in noise," University of California, Marine Physial Laboratory of the Scripps Institution of Oceanography, SIO Ref. 51–39, La Jolla, California, October 4, 1951.

[5] R. M. Fano, "Signal-to-noise ratio in correlation detectors," Tech. Rept. No. 186, Research Laboratory of Electronics, Massahusetts Institute of Technology, Cambridge, Massachusetts, February 19, 1951.

[6] W. B. Davenport, Jr., "Correlator errors due to finite observaion intervals," Tech. Rept. No. 191, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts, March 8, 1951.

[7] Davenport, Johnson, and Middleton, J. Appl. Phys. 23, 377 1952).

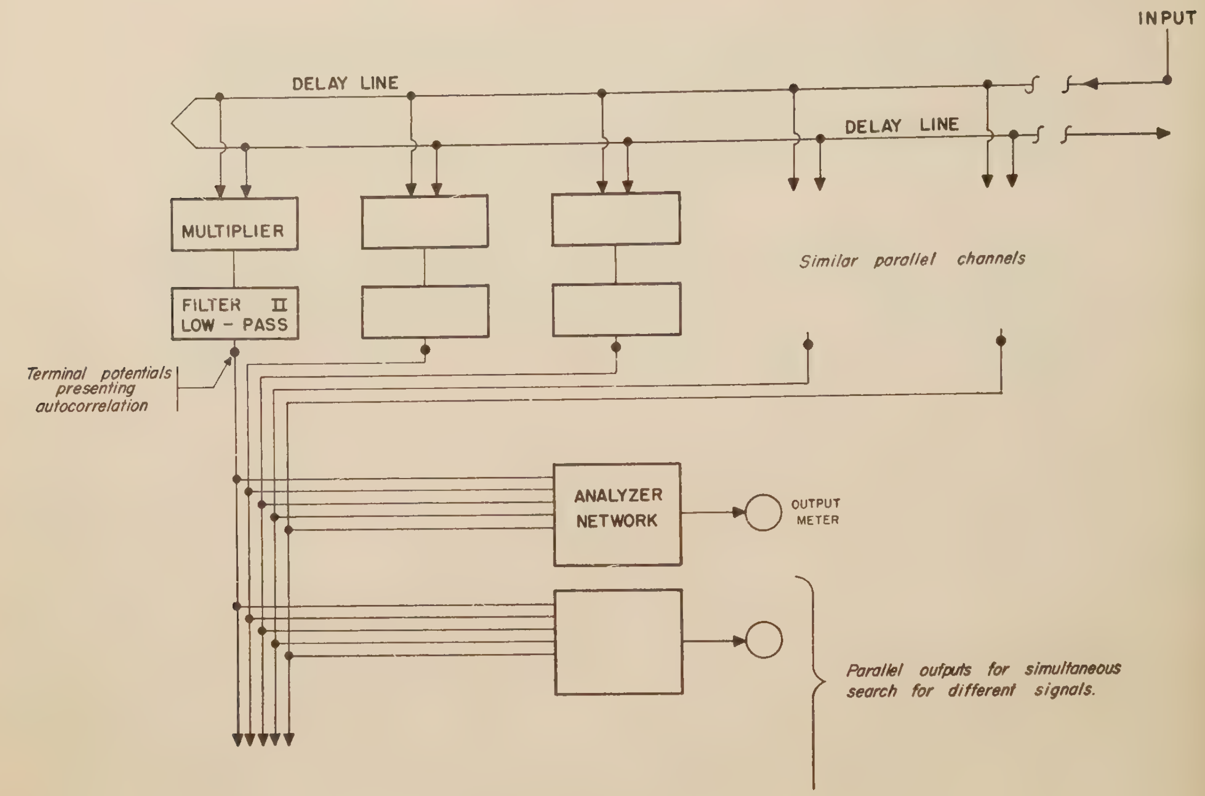
INPUT
DELAY LINE
DELAY LINE
MULTIPLIER
FILTER II
LOW - PASS
Similar parallel channels
Terminal potentials presenting autocorrelation
ANALYZER NETWORK
OUTPUT METER
Parallel outputs for simultaneous search for different signals.

FIG. 2. Autocorrelation system.

this combination being determined by the particular form of component which is to be detected in the correlation function. Again, each filter II must pass, as well as the desired mean or dc output, some unwanted fluctuations which carry through to the final indicating meter.

The filter-rectifier and autocorrelation procedures are quite closely analogous. In each, a quadratic process generates a mean output, which is then isolated as fully as possible by a low pass filter. Each also involves spectral discrimination, in one case preceding and in the other following the quadratic process. For any specific choice of filter I in Fig. 1, a corresponding set of coefficients can be determined for the analyzing network in Fig. 2. This correspondence rests, of course, on the one-to-one relation between power spectra and correlation functions, each being a cosine transform of the other.

Let us consider two systems in which this correspondence between filter I and the analyzing network has been established, and which are also alike in that each quadratic element gives an output of 1 volt per (volt)$^2$ input and the low pass filters II are identical. We suppose both signal and background entering each system to have continuous spectra and Gaussian statistical properties, and that the signal, when present, is statistically independent of the background. These two systems will then produce identical increments of mean (dc) output when any given signal is added to background at each input. Calculations[1] yield the following results:

increment in mean output due to signal for either system

$$=\int_{-\infty}^{\infty} s(\tau)f_1(\tau)d\tau; \tag{1}$$

mean squared fluctuation in output for filter-rectifier system

$$=2\int\int\int a(\tau-\tau_1)a(\tau-\tau_2)f_1(\tau_1)$$
$$\times f_1(\tau_2)f_2(\tau)d\tau_1 d\tau_2 d\tau; \tag{2}$$

mean squared fluctuation in output for autocorrelation

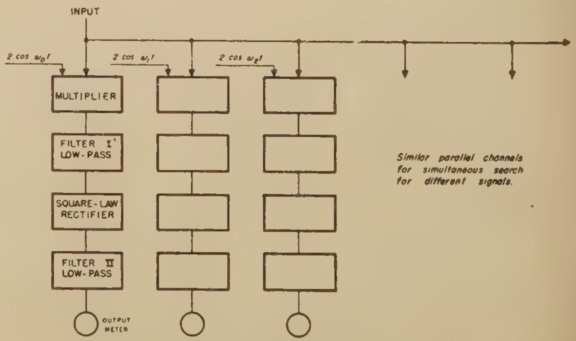
INPUT
2 cos ω₀t
2 cos ω₁t
2 cos ω₂t
MULTIPLIER
FILTER I'
LOW-PASS
SQUARE-LAW
RECTIFIER
FILTER II
LOW-PASS
OUTPUT
METER
Similar parallel channels for simultaneous search for different signals.

FIG. 3. Low frequency heterodyne system.

ystem

$$=2\int\int\int a\left(\tau+\frac{\tau_2-\tau_1}{2}\right)a\left(\tau-\frac{\tau_2-\tau_1}{2}\right)$$
$$\times f_1(\tau_1)f_1(\tau_2)f_2(\tau)d\tau_1 d\tau_2 d\tau. \quad (3)$$

n these expressions $s(\tau)$ and $a(\tau)$ are autocorrelation ınctions of the input signal, and of background, espectively. (The observation time $T$ will be supposed ıfficiently long to make the least detectable signal ower spectrum density well below background. Then ıe important fluctuations are those due only to the ackground.) The functions $f_1(\tau)$ and $f_2(\tau)$ characterize ıe filters I and II, respectively. Each may be defined s the autocorrelation of the filter output when the ıput is white noise of unit power spectrum density ıormalized over $-\infty \leq f \leq \infty$). An equivalent defini- on involving the filter response $I(t)$ to unit impulse t $t=0$ is

$$f(\tau)=\int_{-\infty}^{\infty} I(t)I(t+\tau)dt. \quad (4)$$

The right side of Eq. (1) when applied to the filter- ectifier process is a measure of the power (from the gnal) transmitted through filter I. Applied to the utocorrelation process, the integral is replaced by a iscrete sum which constitutes a definition of the output f the analyzing network in response to a set of inputs epresented by $s(\tau)$. The coefficients $f_1(\tau)$ are charac- eristic of the analyzing network and indicate the way ı which it is related to filter I.

The chief result of this discussion is that the expres- ons given in (2) and (3), although in general differing ısually, if not always, in favor of the filter-rectifier ystem), become identical in the limit of very low ut-off frequency for filter II, corresponding to very ong observation time $T$. In this case, the common esult can be transformed to a very simple expression: ıean squared fluctuation for long averaging time, for ither system,

$$=4\bar{f}_2\int_{-\infty}^{\infty} A^2(f)\,\mathfrak{f}_1^{\,2}(f)df. \quad (5)$$

Iere $A(f)\,\mathfrak{f}_1(f)$ represents the power spectrum density, ue to background, transmitted by filter I (normalized ver the range $-\infty \leqq f \leqq \infty$), and $\bar{f}_2$ is an effective ıt-off frequency for filter II.

Thus for long observation time $T$, we conclude that ıe conventional filter-rectifier system is fully as sensi- ve a detector as the alternative involving computation f a complete autocorrelation function, although the ıstrumentation required by the latter scheme is a ırge order of magnitude more complex if only signals f a single spectral character are being sought. The two ıethods become more nearly comparable in instru- ıental complexity if the search is to cover a wide array f different signals. However, in any case, it seems fair to say that the scheme of Fig. 2 will not be put to practical use without substantial advance beyond the present state of the art of correlator design. The more immediately useful result is the conclusion that simpler autocorrelation procedures, involving only one or a few values of the time delay $\tau$, cannot be expected to do as well as the standard filter-rectifier process.

It may be noted that the comparison of these two systems bears closely on the question posed by Davenport, Johnson, and Middleton,[7] of the comparative time required for the determination of a power spectrum directly by spectral analysis, as against indirectly through the correlation function. These writers do not clearly distinguish between the time required for sufficient data to enter the system, which is an essential time, and the time required to perform successively operations which can in principle be performed simultaneously, or with arbitrarily high speed, which is time required by cost or convenience. The first of these aspects, essential time or quantity of data required, is the only one treated here. If in Fig. 1 the filters I are supposed to be narrow and contiguous, the set of dc output meter readings constitutes a finitely resolved power spectrum of the input, and if Fig. 2 represents a corresponding system receiving the same input, its output meters will give identical dc information. The fluctuations are still given by Eq. (5), or by (2) and (3), and we find the systems equivalent as power spectrum analyzers if the available sample of data is sufficiently large.

Another process, shown in Fig. 3, has also been studied. This is appropriate for a signal whose spectrum is continuous, but confined to a narrow band. The input is multiplied by a local oscillation of single frequency within the signal band, then fed to a low pass filter I′, which acts analogously to filter I in Fig. 1. The succeeding components also correspond. The operation of the multiplier and filter I′ will be called heterodyning to low frequency. It should be remarked, however, that if a dc output were generated by the multiplication, the same operation would be called cross correlation. The calculated over-all performance of Fig. 3 is very closely parallel to that of Fig. 1, except that the least detectable input signal power is greater by a factor $2^{\frac{1}{2}}$ in the low frequency heterodyne process. This is apparently a price that must be paid if the band pass filter I is replaced by a low pass filter I′, which in some circumstances may have a practical advantage.

The superiority of cross correlation with a local sinusoid over simple autocorrelation (with a single delay) for signal detection has been noted in the literature.[2,5] This type of cross correlation has a detection threshold quite comparable to those of the systems of Fig. 1 and Fig. 3.[†] Simple autocorrelation tends to fall far short of all three; only the more elaborate procedure of Fig. 2 provides a fourth method of comparable sensitivity.

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[†] For an input proportional to $\cos\omega_0 t$, the threshold input powers are as $1:2:2^{\frac{1}{2}}$ in the order cross correlation: Fig. 1: Fig. 3. In this case Fig. 3 is not inferior to Fig. 1, because the input and local signals agree in phase.

A simple summary of some aspects of these results can be stated in terms of a signal-to-noise improvement ratio. This we define as the quotient of signal-to-noise ratio at output to that at input, when the latter is a power ratio and the former a voltage ratio, of dc increment due to signal, to rms fluctuation due to background. Improvement ratios defined in this way, for the case of narrow-band signal in broad-band noise, with long observation time $T$, can be expressed[1] (with some simplifying approximations) in terms of three effective band widths: $\beta$ for input background, $\bar{f}_1$ for filter I (assumed not narrower than the input signal spectrum), and $\bar{f}_2$ for filter II. (In case the action of filter II is replaced by a running arithmetic average using equal weights over a time interval $T$, then $\bar{f}_2 = 1/(2T)$. For either filter-rectifier or autocorrelation system (Fig. 1 or 2) the over-all improvement ratio is
$\beta/(2\bar{f}_1\bar{f}_2)^{\frac{1}{2}}$. For the filter-rectifier process this may b
separated into two factors, $(\beta/2^{\frac{1}{2}}\bar{f}_1)$ and $(\bar{f}_1/\bar{f}_2)^{\frac{1}{2}}$, th
first of which can be ascribed to filter I plus rectifie
and the second to filter II. For the autocorrelatio
process the same over-all improvement may be sep
rated into a factor $(\beta/\bar{f}_2)^{\frac{1}{2}}$ characterizing the effect of
single correlator channel, and a second factor $(\beta/2\bar{f}_1$
showing the gain afforded by the analyzing network
combining the many correlator outputs.

The over-all improvement ratio $\beta/(2\bar{f}_1\bar{f}_2)^{\frac{1}{2}}$ is increase
by reducing the values of $\bar{f}_1$ and $\bar{f}_2$. $\bar{f}_2$ always has
lower limit of order $1/(2T)$ when $T$ is (as before) th
allowed detection time. The lower limit of $\bar{f}_1$ will be
the order of either the input signal band width,
$1/(2T)$, whichever is greater. The former case is assume
in the preceding paragraph and leads to over-all im
provement proportional to $T^{\frac{1}{2}}$. In the latter case $\bar{f}_2$
no longer small compared to $\bar{f}_1$, but of the same orde
or filter II is omitted altogether, and the over-a
improvement is of order $\beta/\bar{f}_1$, proportional to $T$.

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SHEPARD, FRANCIS P. and DONALD B. SAYNER. Longshore and coastal currents at Scripps Institution pier. Bull. Beach Eros. Bd., Wash., vol. 7, no. 1, pp. 1-9, 1953. (Unavailable for exchange.)

**615**

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# UPPER CRETACEOUS, TERTIARY, AND RECENT PLANKTONIC FORAMINIFERA FROM MID-PACIFIC FLAT-TOPPED SEAMOUNTS

BY

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# UPPER CRETACEOUS, TERTIARY, AND RECENT PLANKTONIC FORAMINIFERA FROM MID-PACIFIC FLAT-TOPPED SEAMOUNTS

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ABSTRACT—Foraminifera discussed in this paper were collected by the 1950 Scripps Institution-U. S. Navy Electronics Laboratory Mid-Pacific Expedition. Five flat-topped seamounts ("guyots" of Hess, 1946) were dredged and cored in an area between 600 and 1100 miles west of Hawaii.

The following faunas have been identified:

Basaltic gravel layers in a core at 2050 fathoms near one of the guyots contain an Upper Cretaceous (Campanian-Maestrichtian) fauna including species of *Globotruncana*, striate *Gümbelina*, and *Ventilabrella*, mixed with Tertiary and Recent species.

An upper Paleocene fauna dominated by *Globorotalia velascoensis* occurs in indurated *Globigerina* ooze on top of a second guyot.

Two cores taken on top of another guyot contain a lower-middle Eocene *Globigerina* ooze planktonic assemblage dominated by *Globorotalia aragonensis* and with *Hantkenina mexicana* to within an inch of the top of the core.

Conclusions are that the mixed Cretaceous-Recent fauna and the gravel were transported by turbidity currents to their present location and that the Eocene ooze on top of one guyot is due to non-accumulation of later planktonic sediments.

The Foraminifera date the truncation of one guyot as pre-Upper Cretaceous and two others as pre-Paleocene-Eocene, which generally supports the evidence provided by the "middle" Cretaceous reef coral rudistid fauna dredged from these guyots.

Geographic ranges of many Upper Cretaceous and Tertiary planktonic index species have now been extended into the Middle Pacific. These forms will be useful in dating and solving problems of the sedimentation of deep-sea sediments.

## PREFACE

THE MATERIAL on which this paper is based was collected by the 1950 Scripps Institution of Oceanography-U. S. Navy Electronics Laboratory Expedition to Bikini (short name: MidPac). One of the objectives of the expedition was to explore the topography of the Pacific Ocean bottom, especially in areas where there were known flat-topped seamounts ("guyots" of Hess, 1946).

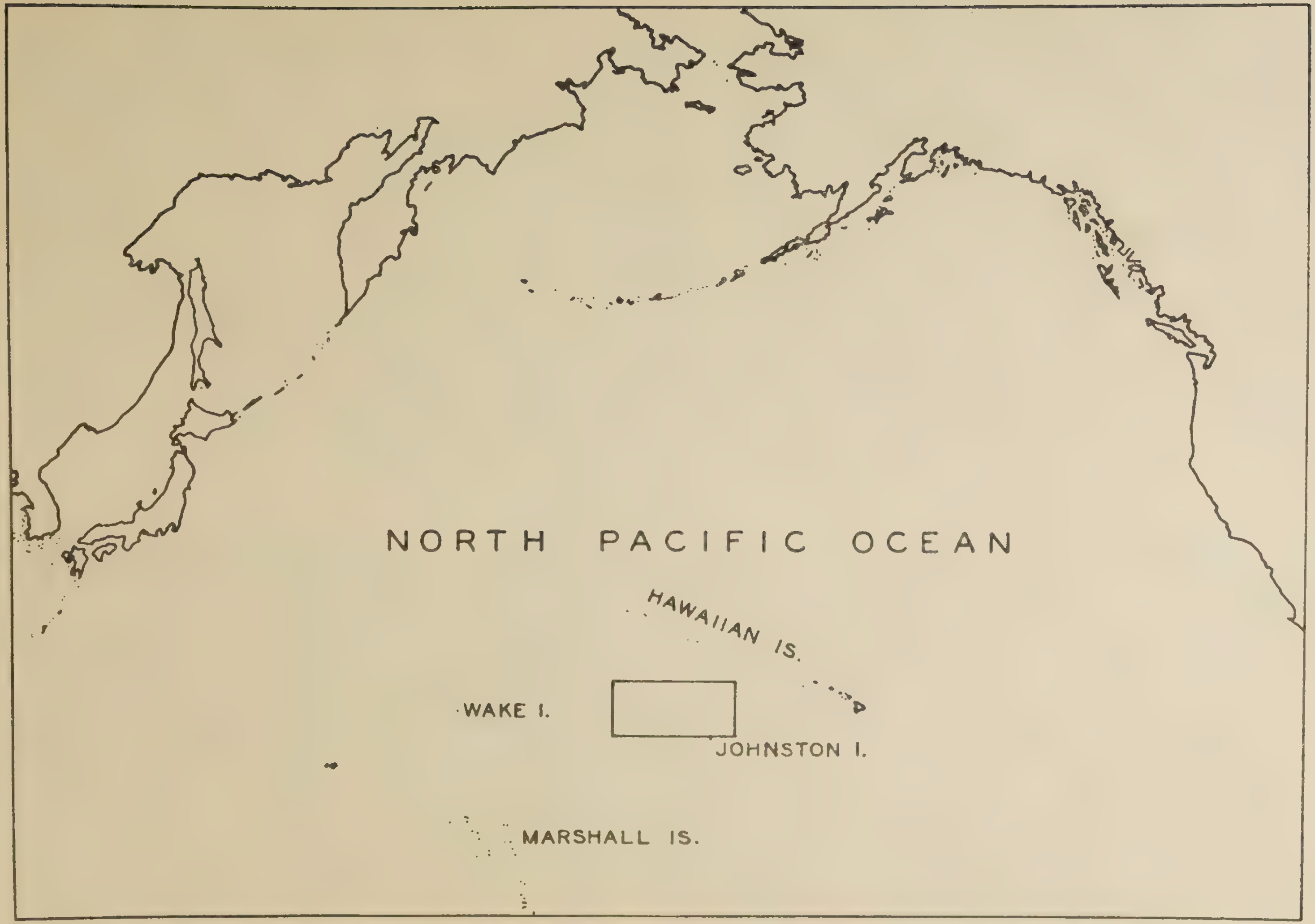
West of Hawaii the MidPac Expedition explored five flat-topped seamounts which are peaks of a great submarine range extending from Necker Island in the Hawaiian Islands to the vicinity of Wake Island (fig. 1). This great submarine range has been named the "Mid-Pacific Mountains." The results of this exploration will be discussed in detail in other reports, but will be summarized here for necessary background.

Echo sounder surveying, dredging, and coring on the guyots revealed that they are the topmost peaks of a basaltic submarine range. These flat-topped seamounts have side slopes approximately 20° near the top. The sides are concave upward with perceptible breaks in slope between the upper side slopes and the flat tops at depths ranging from 720 to 1150 fathoms. The profiles are symmetrical.

Rounded sand grains, pebbles, cobbles, and boulders of olivine basalt were dredged from the tops and below the breaks in slope on the guyots. Sandstone from a basaltic source was dredged on two of the features. Calcium carbonate was present in the form of organic limestone and *Globigerina* ooze.

Dredge hauls near the breaks in slope on two guyots brought up a well-integrated fossil fauna of reef coral, rudistids, stromatoporoids, gastropods, pelecypods, and an echinoid. The age of this assemblage is Cretaceous (Aptian to Cenomanian); the affinities are with the faunas of the Tethyan Province.

The conclusions from the above evidence


NORTH PACIFIC OCEAN
HAWAIIAN IS.
WAKE I.
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MARSHALL IS.

Fig. *1*—Index map showing the area (outlined by the rectangle) in which flat-topped seamounts were sampled.

are that during Cretaceous time there was a chain of basaltic islands in the Mid-Pacific where the submarine range now lies; that these islands were wave eroded to flat banks on which a reef coral-rudistid fauna found lodgement. The reef coral was apparently present as banks on and among the erosional debris and the guyots were never fully developed atolls. The truncated volcanic mountains and ridges were submerged during Cretaceous time below the zone of reef coral growth; subsequently the guyots sank to the present depth of around 900 fathoms.

The subject materials of this paper are the fossil planktonic Foraminifera which occur on all five of the sampled guyots.

## INTRODUCTION

The planktonic Foraminifera have been largely neglected as primary tools for regional and inter-regional correlation. In recent years, however, several authors have stressed the value of these forms for long-distant correlation (Glaessner, 1937 and 1945; LeRoy, 1948; Stainforth, 1948 and 1950; Bronnimann, 1950, Grimsdale, 1951). A good index fossil should be abundant, geographically widespread, have a short stratigraphic or geologic range, and distinct morphology. The planktonic Foraminifera are widespread and abundant because of large oceanic water masses of comparable ecologic conditions.

Many planktonic Foraminifera have a short range in geologic time and many have distinct morphology. As is well known in micropaleontology, however, these two aspects of planktonic forms are the principal difficulties to the present use of the planktonics in long range correlations. There remains a tremendous amount of work to unravel the synonyms, mistakes in identification, and to refine the "waste-basket" species so that they can be used stratigraphically. Each genus of planktonic Foraminifera should be monographed. When this is accomplished it will be possible to correlate the marine sediments from the Upper Cretaceous to Pliocene on a world-wide basis by using planktonic Foraminifera. In order to establish a sequence of planktonic foraminiferal index fossils, any evidence on their geographic or geologic distribution is desirable.

This paper contributes toward a solution of the problems discussed above by extending the geographic ranges of a number of planktonic index fossils to the Middle Pacific. The establishment of planktonic index fossils for the Pacific Ocean area is of particular interest to the writer and his colleagues for the dating of deep-sea sediments which are normally collected on the various Scripps-Navy Electronics Laboratory expeditions. The ecology of Foraminifera has proved useful in solving problems of sedimentation (an excellent example being Phleger's 1951 paper on displaced foraminiferal faunas). In the area of the flat-topped seamounts all of the assemblages are planktonic, but the ages of the various index fossils have proved extremely useful in studying the sedimentation on and around the guyots.

Data in connection with the sampling stations discussed in this paper are summarized in table 1.

*Acknowledgments.*—The writer appreciates the helpful suggestions of the following persons who critically read the manuscript: R. S. Dietz, H. W. Menard, F. B. Phleger, Miss F. L. Parker, M. N. Bramlette, H. E. Thalmann, J. J. Graham, Miss Ruth Todd, and Miss Jean F. Peirson.

At the U. S. Navy Electronics Laboratory, San Diego, the writer appreciates the help of the following persons in preparation of the manuscript: photographs of the fossils by J. H. Sneed, help in assembling the plates and manuscript by Mrs. Shirley A. Fisher and Mrs. Joan McAllister, typing by Mrs. Anna L. Moore, and drafting by G. A. Prible.

The writer appreciates the assistance and helpful suggestions of the following persons who verified the writer's identification of several species: Miss Ruth Todd, Hans Bolli, O. L. Bandy, and C. D. Ovey. A. R. Loeblich kindly sent the writer several type specimens from the U. S. National Museum.

At the Marine Foraminifera Laboratory, Scripps Institution of Oceanography, the writer was materially aided in the study of the faunas and in preparation of the plates by Miss F. L. Parker, and by the facilities

TABLE 1.—DATA OF MIDPAC EXPEDITION SAMPLING STATIONS

| MP Station | Approximate Positions | | Depth (fathoms) | Sampler | Sample Description | Field Notes and Remarks |
|---|---|---|---|---|---|---|
| | N. Lat. | W. Long. | | | | |
| 25 E-1 | 19 40 | 168 32 | 931 | Phleger corer | 31″ core *Globigerina* ooze | Just above break in slope on Horizon Guyot; Eocene fauna |
| 25 E-2 | 19 40 | 168 32 | 950 | Phleger corer | 28″ core *Globigerina* ooze | Just above break in slope on Horizon Guyot; Eocene fauna |
| 26 A-3 | 19 25 | 171 00 | 720–770 | Chain-bag dredge | $MnO_2$ coated fossil *Globigerina* ooze rock; olivine basalt boulders with rounded corners, sandstone pebble, silicified limestone, olivine basalt chips: all covered by $MnO_2$. | Dredging across break in slope; fossil *Globigerina* ooze rock contains lower-middle Eocene Foraminifera fauna. |
| 27-2 & 2P | 19 34 | 171 54 | 2050 | Piston-type corer with attached Phleger corer (2P) | MP 27-2:3′ core of red clay with two layers of subrounded to angular, uncoated gravel from basaltic source; 27-2P: Phleger core of *Globigerina* ooze and red clay. | Coring in "basin" near Guyot 20171; both cores contained the same Upper Cretaceous to Recent mixed planktonic fauna. |
| 33 C | 17 45 | 174 16 | 910–920 | Chain-bag dredge | Rounded, white, soft rocks composed of foram tests, and finely divided $CaCO_3$ (indurated *Globigerina* ooze); some had black Mn coating. | Dredging near the top center of Hess Guyot. Foraminifera fauna is probable upper Paleocene. |

of the Laboratory which were generously opened to him.

Photographs were retouched by the writer.

Unfortunately, the exact locations of sampling stations cannot be given due to the present policy of the Navy of classifying deep-sea soundings as restricted security information. The locations of all the seamounts concerned, however, are shown on the U. S. Navy Hydrographic Chart No. 0528.

## DESCRIPTION AND DISCUSSION OF THE FAUNAS

*Present-day fauna.*—The present-day fauna in the area investigated (fig. 1) is the tropical and semi-tropical planktonic assemblage of the Pacific previously noted by several authors (Brady, 1884; Cushman, 1910–1916, 1921, 1925; and others).

The following species have been noted in the present-day assemblages which are assumed to be without contamination; these species are the ones referred to as "the present-day tropical Pacific planktonic assemblage."

A count of 300 specimens was made in one sample from Cape Johnson Guyot and the percentage of occurrence of each species is indicated opposite the species name.

| Species | Percentage of Occurrence |
|---|---|
| *Globigerina bulloides* d'Orbigny | 3 |
| *G. digitata* Brady | −1 |
| *G. eggeri* Rhumbler | 1 |
| *G. hexagona* Natland | 2 |
| *G. inflata* d'Orbigny | −1 |
| *G. quinqueloba* Natland | −1 |
| *G. subcretacea* Lomnicki | 1 |
| *G.* cf. *G. venezuelana* Hedberg | −1 |
| *Globigerinita glutinata* (Egger) | 5 |
| *Globigerinoides conglobata* (Brady) | 12 |
| *G. rubra* (d'Orbigny) | 33 |
| *G. sacculifera* (Brady) | 16 |
| *Globorotalia hirsuta* (d'Orbigny) | −1 |
| *G. menardii* (d'Orbginy) | 3 |
| *G. punctulata* (d'Orbigny) | −1 |
| *G. scitula* (Brady) | 1 |
| *G. tumida* (Brady) | 3 |
| *G. truncatulinoides* (d'Orbigny) | 4 |
| *Globigerinella aequilateralis* (Brady) | 5 |
| *Candeina nitida* d'Orbigny | 2 |
| *Orbulina universa* d'Orbigny | 4 |
| *Pulleniatina obliquiloculata* (Parker and Jones) | 3 |
| *Sphaeroidinella dehiscens* (Parker and Jones) | −1 |

*Cores at MP 27.*—Three cores were taken at MP 27 (MidPac Expedition Station No. 27) at 19°34′N. Lat. and 171°54′W. Long. at a depth of 2050 fathoms. This station was in a basin or deep valley which is a reentrant into the south side of the main ridge of the Mid-Pacific Mountains and was about 15 nautical miles from the nearest known guyot. No soundings were available on three sides of MP 27 and consequently the topography surrounding the area is largely unknown.

A piston corer used at this station passed through at least two layers of gravel (fig. 2); the lower bed, at a depth of about 26 inches below the surface was graded with large pebbles of basalt at the bottom of the bed. The total length of this core was about three feet. A Phleger Bottom Sampler, or small corer (Phleger, 1951) was attached to the trip arm of the piston corer and took a 34½ inch core.

An examination of the sand and gravel revealed that it was composed of rounded to subangular sand grains, pebbles, and cobbles of basalt. The Foraminifera of this gravel layer are a mixture of Upper Cretaceous to Recent species. This mixed assemblage occurs with little variation throughout both cores. The Phleger Bottom Sampler takes a relatively undisturbed sample of the surface of the sea floor and the upper part of this core was examined carefully. The upper one inch (the present-day sea bottom) was a white, unconsolidated *Globigerina* ooze which contained the Upper Cretaceous to Recent forms mentioned above. A count of 300 specimens revealed that about 55% were fossil. About 25% of the total specimens counted belong to the genus *Globotruncana* and about 11% to the genus *Gümbelina*. The Upper Cretaceous specimens are as well preserved as the apparently Recent material. This mixed fauna includes many of the well known planktonic index fossils of the Paleocene, Eocene, and later epochs.

In the following lists the mixed fauna will be reported in two parts for clarity.

Upper Cretaceous fauna:
*Globigerina cretacea* d'Orbigny
*Rugoglobigerina rugosa rugosa* (Plummer)
*Globigerinella aspera* (Ehrenberg)
*Globorotalia velascoensis* (Cushman)
*Globotruncana arca* (Cushman)
*G. calcarata* Cushman
*G. caliciformis* (de Lapparent)
*G. canaliculata* (Reuss)
*G. contusa* (Cushman)
*G. fornicata* Plummer
*G. gansseri* Bolli
*G. globigerinoides* Brotzen
*G. marginata* (Reuss)
*G. rosetta* (Carsey)

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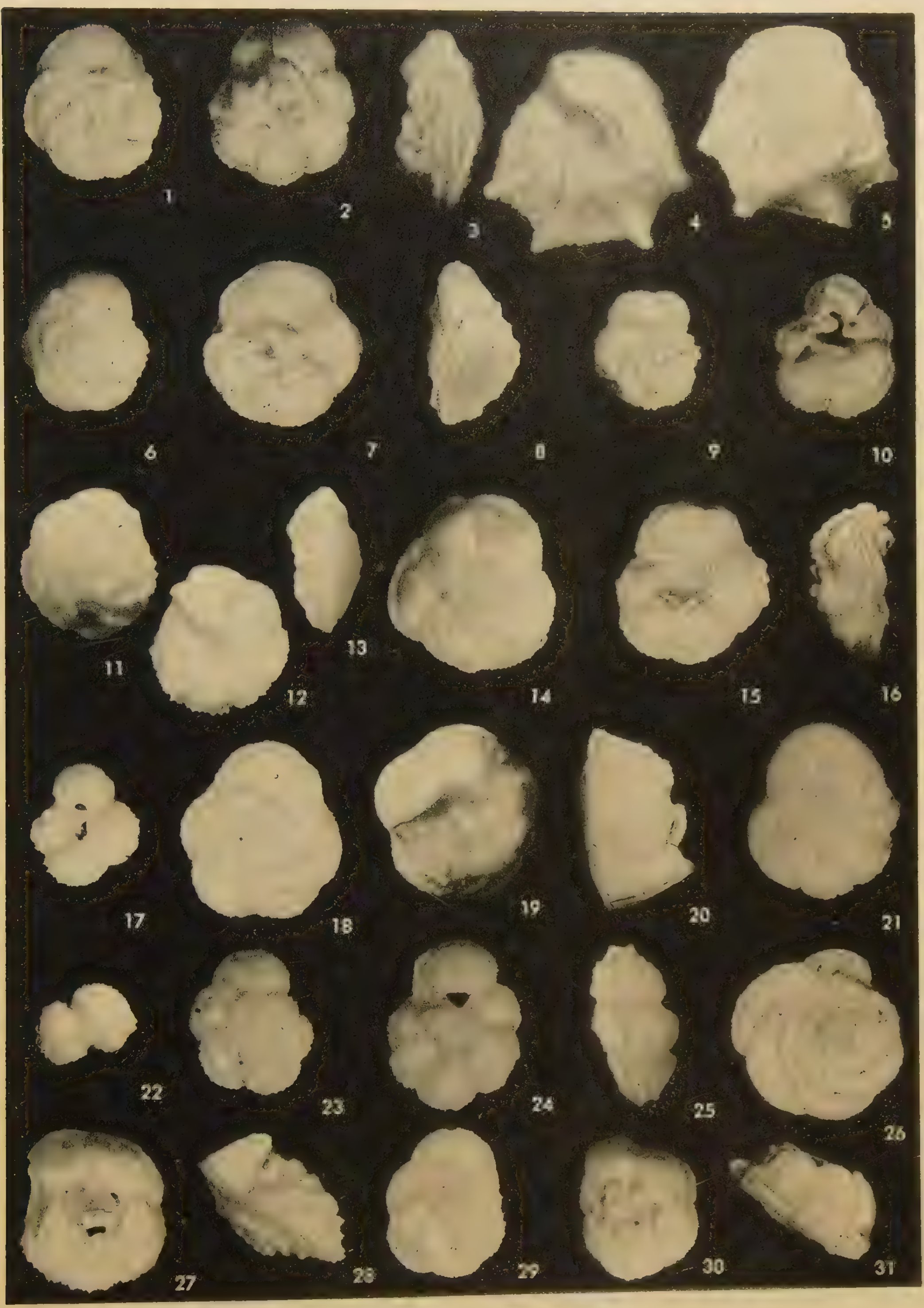
EXPLANATION OF PLATE 29

Species of *Globotruncana* from MP 27; 19° 34′ N. Latitude, 171° 54′ W. Longitude; depth 2050 fathoms.

FIGS. *1–3*—*Globotruncana arca* (Cushman). Three specimens; *1*, dorsal view, ×48; *2*, ventral view, ×46; *3*, side view, ×51. (p. 231)
*4, 5*—*Globotruncana calcarata* Cushman. *4*, ventral view; *5*, dorsal view; ×52. (p. 232)
*6–8*—*Globotruncana caliciformis* (de Lapparent). Three specimens; *6*, dorsal view; *7*, ventral view; *8*, side view; ×47. (p. 232)
*9, 10*—*Globotruncana canaliculata* (Reuss). Two specimens; *9*, dorsal view, ×45; *10*, ventral view, ×53. (p. 232)
*11–13*—*Globotruncana stuarti* (de Lapparent). *11*, dorsal view; *12*, ventral view; *13*, side view; ×53. (p. 233)
*14–16*—*Globotruncana contusa* (Cushman). Three specimens; *14*, dorsal view; *15*, ventral view *16*, side view; ×46. (p. 232)
*17, 22*—*Globotruncana globigerinoides* Brotzen. Two specimens; *17*, ventral view; *22*, side view; ×48. (p. 233)
*18–20*—*Globotruncana gansseri* Bolli. Three specimens; *18*, dorsal view; *19*, ventral view; *20*, side view; ×53. (p. 232)
*21*—*Globotruncana fornicata* Plummer. Dorsal view; ×46. (p. 232)
*23–25*—*Globotruncana marginata* (Reuss). Three specimens; *23*, dorsal view; *24* ventral view; *25*, side view, ×46. (p. 233)
*26–28*—*Globotruncana rosetta* (Carsey). Three specimens; *26*, dorsal view; *27*, ventral view; *28*, side view; ×45. (p. 233)
*29–31*—*Globotruncana ventricosa* (White). Three specimens; *29*, dorsal view; *30*, ventral view; *31*, side view; ×47. (p. 233)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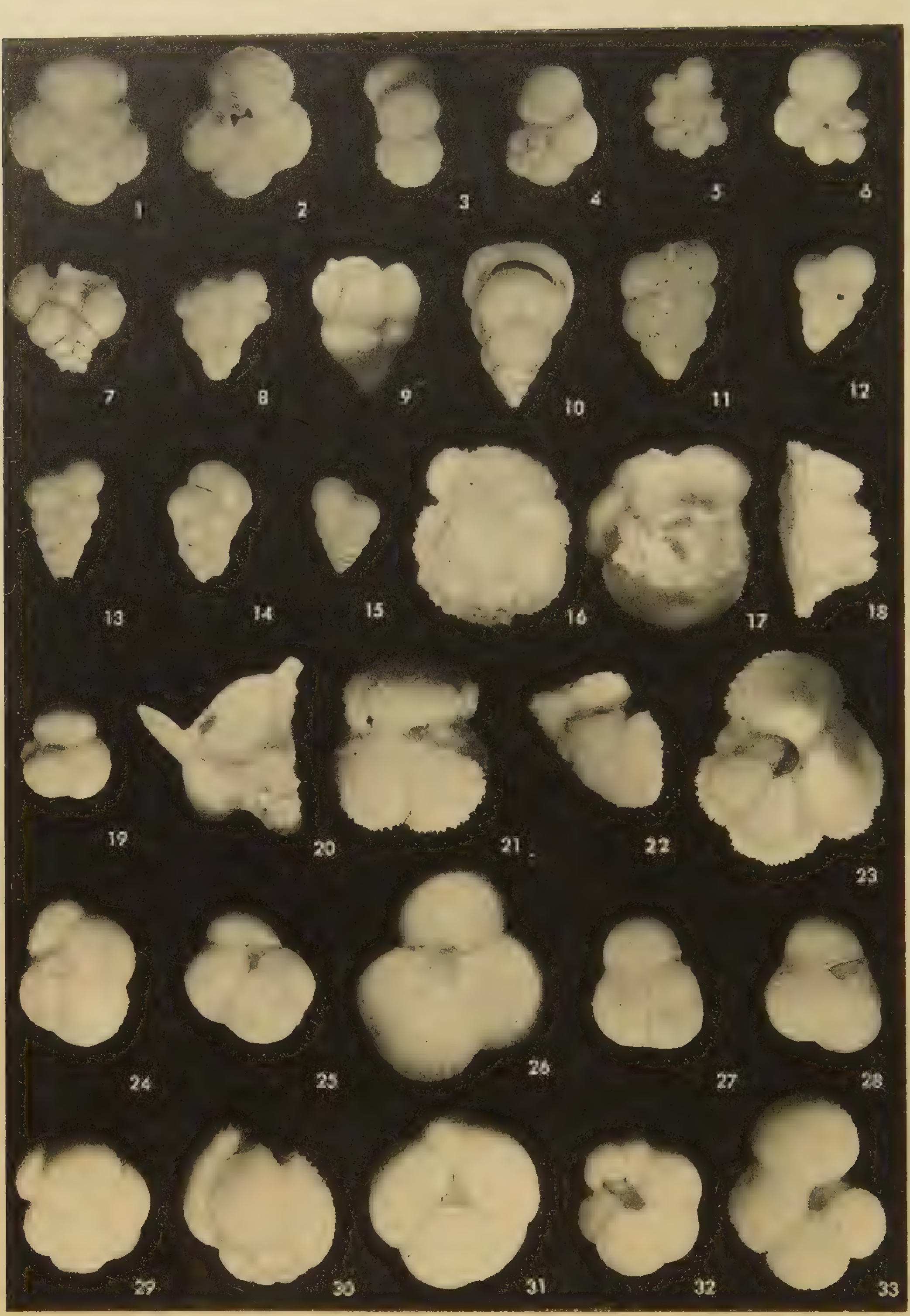
Hamilton, Foraminifera from Pacific seamounts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Hamilton, Foraminifera from Pacific seamounts

*G. stuarti* (de Lapparent)
*G. ventricosa* (White)
*Gümbelina costulata* Cushman
*G. excolata* Cushman
*G. globulosa* (Ehrenberg)
*G. striata* (Ehrenberg)
*G. plummerae* Loetterle
*G. pseudotessera* Cushman
*G. ultimatumida* White
*Pseudotextularia varians* Rzehak
*Ventilabrella austinana* Cushman
*V. carseyae* Plummer

Early Tertiary to Recent fauna:

In addition to the modern tropical Pacific species previously noted (see "present-day fauna") the following Tertiary planktonic species have been identified.

*Globigerina altispira* Cushman and Jarvis
*G. bulloides* d'Orbigny
*G. cretacea* d'Orbigny
*G. pseudobulloides* Plummer
*G. triloculinoides* Plummer
*G. venezuelana* Hedberg
*Globigerinella voluta* (White)
*Globigerinoides mexicana* (Cushman)
*Globorotalia aragonensis* Nuttall
*G. crassata* (Cushman)
*G. crassata* (Cushman) var. *aequa* Cushman and Renz
*G. crassata densa* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)
*G. wilcoxensis* Cushman and Ponton
*Hantkenina alabamensis* Cushman
*Sphaeroidinella multiloba* LeRoy
*S. rutschi* Cushman and Renz
*S. seminulina* (Schwager)
*Eponides trümpyi* Nuttall

*Hess Guyot faunas.*—Hess Guyot[1] (indicated as shallow sounding on U. S. Navy H. O. Chart No. 0528 at 17°45′N. Lat. and

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[1] Hess Guyot is named after Harry H. Hess of Princeton University who discovered it.

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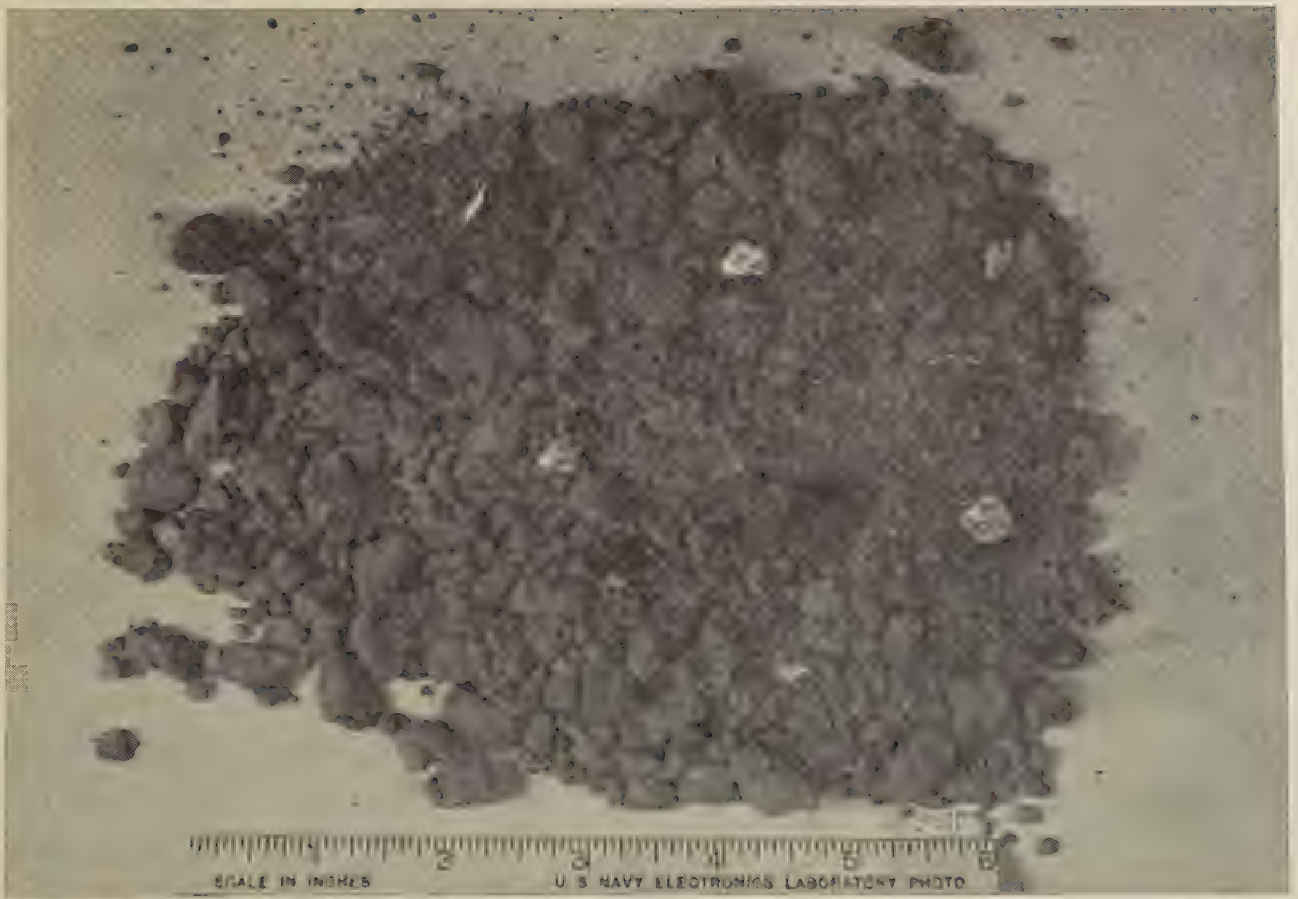
### EXPLANATION OF PLATE 30

Species (in addition to those in Plate 29) from the mixed Upper Cretaceous to Recent fauna from MP 27.

FIGS. *1–3*—*Rugoglobigerina rugosa rugosa* (Plummer) Bronnimann. Three specimens; *1*, dorsal view; *2*, ventral view; *3*, side view; ×51. (p. 227)
*4*—*Nonion micrus* Cole; ×51. (p. 236)
*5*—*Globigerinella aspera* (Ehrenberg); ×53. (p. 226)
*6*—*Globigerinella voluta* (White); ×51. (p. 227)
*7*—*Ventilabrella austinana* Cushman; ×51. (p. 235)
*8*—*Ventilabrella carseyae* Plummer; ×51. (p. 235)
*9*—*Pseudotextularia varians* Rzehak; ×56. (p. 235)
*10*—*Gümbelina plummerae* Loetterle. Side view; ×54. (p. 234)
*11*—*Gümbelina excolata* Cushman. Front view; ×51. (p. 234)
*12*—*Gümbelina costulata* Cushman. Front view; ×51. (p. 234)
*13*—*Gümbelina striata* (Ehrenberg). Front view; ×51. (p. 235)
*14*—*Gümbelina pseudotessera* Cushman. Front view; ×51. (p. 234)
*15*—*Gümbelina globulosa* (Ehrenberg). Front view; ×50. (p. 234)
*16*—*18*—*Globorotalia velascoensis* (Cushman). Three specimens; *16*, dorsal view; *17*, ventral view; *18*, side view; ×52. (p. 231)
*19*—*Globigerina triloculinoides* Plummer. Ventral view; ×51. (p. 223)
*20*—*Hantkenina alabamensis* Cushman. Side view of fragment; ×55. (p. 229)
*21, 22*—*Globorotalia crassata* (Cushman) var. *aequa* Cushman and Renz. Two specimens; *21* ventral view; *22*, dorsal view; ×52. (p. 230)
*23*—*Globorotalia velascoensis* (Cushman). Ventral view of specimen from Hess Guyot; ×48. (p. 231)
*24, 25*—*Sphaeroidinella rutschi* Cushman and Renz. Two specimens; *24*, dorsal view, ×53; *25*, ventral view, ×50. (p. 228)
*26*—*Sphaeroidinella multiloba* LeRoy. Ventral view; ×52. (p. 228)
*27, 28*—*Sphaeroidinella seminulina* (Schwager). Two specimens; *27*, dorsal view; *28*, ventral view. ×54. (p. 228)
*29, 30*—*Globigerina altispira* Cushman and Jarvis. Two specimens; *29*, side view; *30*, side view. ×55. (p. 220)
*31*—*Globigerina venezuelana* Hedberg. Ventral view; ×59. (p. 223)
*32*—*Globigerina subcretacea* Lomnicki. Ventral view; ×53. (p. 223)
*33*—*Globigerina bulloides* d'Orbigny. Ventral view; ×53. (p. 221)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U S NAVY ELECTRONICS LABORATORY PHOTO

Fig. 2—Basaltic gravel and sand mixed with red clay and containing a mixed Upper Cretaceous to Recent foraminiferal fauna. Sample taken from the 30½ to 34½ inch division of the core from MP 27-2 from a depth of 2050 fathoms

174°16′W. Long.) is a peak on the south side of the main ridge of the Mid-Pacific Mountains. This guyot has a distinctly flat top with a shallowest sounding of 902 fathoms. At Station MP 33 C near the center of this flat-topped feature the dredge brought up a large amount of rounded, soft, but indurated fossil *Globigerina* ooze which ranged in size from pellets to boulders a foot in length (fig. 3). When this haul came up over the side of the ship there was a stream of milky white water pouring out of the dredge. The fragments of indurated *Globigerina* ooze apparently were rounded in the dredge during the mile long haul to the surface. Scattered remnants of a manganese dioxide crust support this belief.

The indurated *Globigerina* ooze described above yielded an uncontaminated, extremely well-preserved, planktonic assemblage of probable Paleocene age. The following species have been identified:

*Globigerina* aff. *G. angulata* White
*G. bulloides* d'Orbigny
*G. compressa* Plummer
*G. cretacea* d'Orbigny
*G. eocaena* Gümbel
*G. pseudobulloides* Plummer
*G. triloculinoides* Plummer
*Globigerinella pseudovoluta* Bandy
*Globorotalia crassata* (Cushman)
*G.* aff. *G. inconspicua* Howe
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)
*Gümbelina* aff. *G. glabrans* Cushman
*G. globulosa* (Ehrenberg)
*G. ultimatumida* White
*Eponides trümpyi* Nuttall

Small pipe dredges with canvas bags attached which trailed behind the main chain-bag were used during three dredge hauls to gather samples of the *Globigerina* ooze. These samples contained the modern Pacific tropical fauna plus the following rare planktonic index fossils:

*Globigerinoides mexicana* (Cushman)
*Globigerina ouachitaensis* Howe and Wallace
*Globorotalia aragonensis* Nuttall
*G. crassata* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)

Five cores were taken on Hess Guyot with the Phleger Bottom Sampler. These cores ranged in length from 4¾ inches to a little over 38 inches. At each station the core was essentially composed of the modern Pacific tropical foraminiferal fauna plus the following rare, fossil planktonic index fossils:

*Globigerina triloculinoides* Plummer
*Globorotalia aragonensis* Nuttall
*G. crassata* (Cushman)
*G. crassata densa* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)
*Gümbelina cubensis* Palmer

*Faunas on Horizon Guyot.*—Horizon Guyot, named after the Scripps motor vessel *Horizon* is a volcanic ridge whose northeast end is indicated on Navy H. O. Chart 0528 at 19°40′N. Lat., 168°32′W. Long. A saddle more than 1200 feet deep divides the ridge near its west end so that the western end appears as an oval seamount. This seamount has a break in slope between the flat top and upper side slopes at depths between 935 and 950 fathoms. Two dredge hauls, one snapper sample and five small cores were taken on Horizon Guyot.

Two cores of particular interest were taken on a 2 degree slope just above the break in slope at the edge of the guyot. Each core contained the same pure Eocene fauna except for the top 1 to 2 inches which contained a mixture of Eocene species and modern tropical Pacific species. The present-day sea bottom on the top of Horizon Guyot therefore is a mixture of Eocene and Recent species. One core (MP 25 E-2) was 28 inches long and was a pure, unconsolidated Eocene *Globigerina* ooze from the bottom to within two inches of the top. The second (MP 25 E-1) was 31 inches long and was the same except that the bottom four inches contained a mixture of Recent and Eocene species similar to the topmost portion. This bottom mixture could have been sampled if the core hit the bottom a second time before withdrawal to the surface, or if the deposit cored was a slump. Both cores were taken at the same station but not at the same place because of drift of the ship on station.

The following Eocene fauna was present

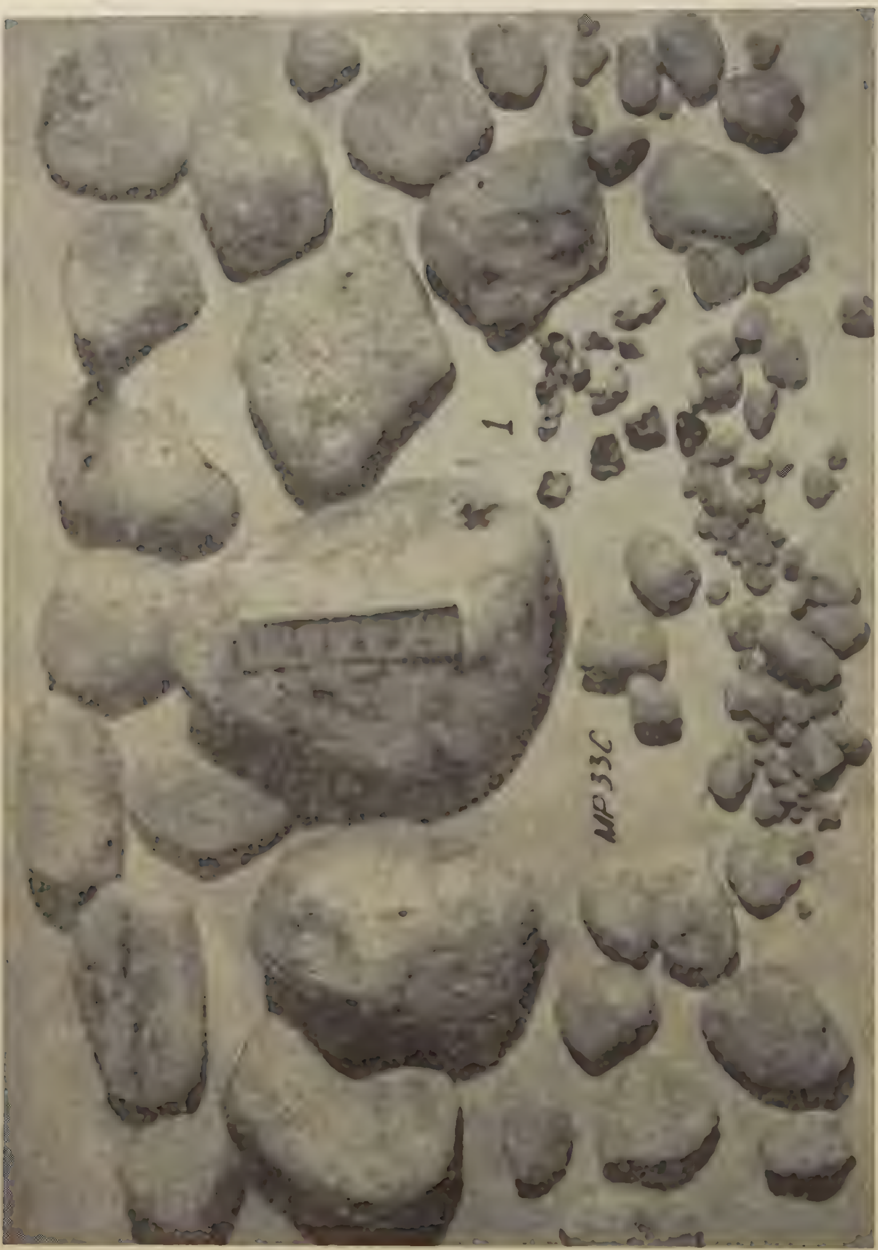

FIG 3—Dredge haul from the center of the top of Hess Guyot (MP 33 C) The rounded rocks are composed of soft but indurated *Globigerina* ooze and contain a Paleocene foraminiferal fauna.

in both cores with almost no variation:

*Globigerina apertura* Cushman
*G. bulloides* d'Orbigny
*G.* aff. *G. eocaena* Gümbel
*G. linaperta* Finlay
*G. mckannai* White
*G. ouachitaensis* Howe and Wallace
*G. ouachitaensis* Howe and Wallace var. *senilis* Bandy
*G. orbiformis* Cole
*G. rotundata* d'Orbigny var. *jacksonensis* Bandy
*G. triloculinoides* Plummer
*Globigerinoides nuttalli* Hamilton, n. sp.
*G. mexicana* (Cushman)
*Globigerinella pseudovoluta* Bandy
*Globorotalia aragonensis* Nuttall
*G. centralis* Cushman and Bermudez
*G. crassata* (Cushman)
*G. crassata densa* (Cushman)
*G.* aff. *G. inconspicua* Howe
*Gümbelina cubensis* Palmer
*G. venezuelana* Nuttall
*Hantkenina mexicana* Cushman var. *aragonensis* Nuttall
*Hastigerinella eocanica* Nuttall
*H. eocanica aragonensis* Nuttall
*Eponides trümpyi* Nuttall

The following species were collected from cracks inside manganese-covered boulders of volcanic rock cemented by fine-grained organic limestone which were dredged from the top of Horizon Guyot.

*Globigerina triloculinoides* Plummer
*Globorotalia aragonensis* Nuttall
*G. crassata* (Cushman)
*G. crassata densa* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)
*Gümbelina cubensis* Palmer
*G. globulosa* (Ehrenberg)
*Sphaeroidinella seminulina* (Schwager)

*Faunas of Cape Johnson Guyot.*—Cape Johnson Guyot, named after the USS *Cape Johnson*, the ship which took the original soundings resulting in the discovery of both Hess and Cape Johnson Guyots, is a flat-topped peak on the south side of the main ridge of the Mid-Pacific Mountains. Its position is indicated as a shallow sounding on the Navy H. O. Chart 0528 at 17°05′N. Lat. and 177°15′W. Long. The shallowest sounding was 925 fathoms near the center of the flat top.

Four cores of *Globigerina* ooze ranging in length from 10 inches to 108 inches were taken by the Phleger Bottom Sampler and piston corer at each of four stations just above and below the break in slope and near the center of Cape Johnson Guyot. Each core was essentially composed of modern tropical Pacific species, but in each fossil planktonic Foraminifera are rare. The fossil specimens usually could be distinguished by their brownish-white color in contrast to the white color of most of the Recent species.

The following fossil species were observed in these Cape Johnson cores:

*Globigerina altispira* Cushman and Jarvis
*G. apertura* Cushman
*G. linaperta* Finlay
*G. triloculinoides* Plummer
*G. venezuelana* Hedberg
*Globorotalia aragonensis* Nuttall
*G. crassata* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)
*Gümbelina cubensis* Palmer
*G. globulosa* (Ehrenberg)

The following fossil planktonic species were taken from cracks inside manganese dioxide coated limestone rocks dredged from Cape Johnson Guyot:

*Globorotalia crassata* (Cushman)
*G. velascoensis* (Cushman)
*G. velascoensis* (Cushman) var. *acuta* (Toulmin)

*Fauna on Guyot 19171.*—Guyot 19171 (numbered after the nearest lines of latitude and longitude) is indicated as a shallow sounding on the Navy H. O. Chart No. 0528 at 19°25′ N. Lat. and 171°00′W. Long. It has a flat top on which the shallowest sounding was 668 fathoms.

A dredge haul (MP 26A-3) across the break in slope brought up a rounded boulder of indurated *Globigerina* ooze completely covered by a manganese coating which was 6 mm. thick on top, but on the bottom was merely a black discoloration.

This indurated *Globigerina* ooze boulder has a planktonic lower Eocene fauna the tests of which were affected by solution and reprecipitation. The following species have been identified:

*Globigerina triloculinoides* Plummer
*Globorotalia aragonensis* Nuttall

*G. centralis* Cushman and Bermudez
*G. crassata* (Cushman)
*G. crassata densa* (Cushman)
*G. wilcoxensis* Cushman and Ponton

## DISCUSSION OF RESULTS AND CONCLUSIONS

Globotruncana.—*Globotruncana* Cushman, 1927, is an extinct genus of Foraminifera with a world-wide distribution. The species are considered to be the best foraminiferal index fossils of the Upper Cretaceous. Beds containing *Globotruncana* probably are not older than Cenomanian, and all species of the genus die out at the end of the Maestrichtian according to Glaessner (1945). *Globotruncana* species are found in the Tethyan Province in Mexico, the Caribbean and Gulf Coast and adjacent regions, the Alps, Apennines, North Africa, Southeastern Africa, Greece, Caucasus, the Middle East, New Guinea, Celebes, Australia and New Zealand, and have recently been reported from California (Glaessner, 1945; Thalmann, 1934 and 1942a; Bandy, 1951). The genus is considered to have been planktonic due to its common occurrence with species of *Globigerina* and *Globorotalia* (Glaessner, 1945) and its form of large, frequently inflated chambers. The abundance of species of *Globotruncana* in places where purely planktonic assemblages are likely to occur (as in the Mid-Pacific guyot area) is important evidence of its existence as a planktonic organism.

*Globotruncana* is closely allied to *Globorotalia* and *Globigerina* (Cushman, 1948). *Globigerina rugosa* Plummer with its umbilical plate and *Globotruncana globigerinoides* Brotzen which is no more than a double-keeled *Globigerina* are intergrading forms between *Globigerina* and *Globotruncana* which occur in the Mid-Pacific faunas and clearly illustrate the evolution of *Globotruncana* from *Globigerina*.

Species of *Globotruncana* are assumed to have been tropical and semi-tropical forms because of their occurrence in the Cretaceous Tethys Sea which is known to have been a warm water area due to common occurrences of reef coral.

Species of *Globotruncana* which are of common occurrence in the cores at MP 27 are also common in Mexico, the Gulf Coast and Caribbean regions (Cushman, 1946). This is additional evidence of the close faunal affinity of the Cretaceous guyots faunas with those of the Gulf Coast and adjacent regions (which is in accord with the conclusions reached regarding the megafossils) and which is further proof of the presence of the Tethys Sea across Mexico and Central America.

The age of the guyot *Globotruncana* is Campanian-Maestrichtian. The overlapping ranges of the identified species are shown in the range chart (fig. 4).

Gümbelina.—*Gümbelina* Egger, 1899, is an extinct genus with world-wide distribution in the tropical and semi-tropical Tethys Sea. The genus occurs commonly in Upper Cretaceous beds where the striate forms die out at the end of the Maestrichtian; the genus persisted into the Tertiary and finally died out in Oligocene time. Cushman (1938) and Glaessner (1945), among other authors, think that *Gümbelina* was a pelagic form because of its thin-walled and globular chambers and its common occurrence in planktonic faunas with *Globigerina* and *Globorotalia*, the genera making up the vast bulk of modern pelagic deposits.

Three groups of species of *Gümbelina* are known from the Mid-Pacific guyots. The oldest is from the cores at MP 27. This fauna contains many species which occur in the Gulf Coast and adjacent regions in the Upper Cretaceous. These species of *Gümbelina* occur with the species of *Globotruncana* discussed previously and are of the same age.

The second group of species of *Gümbelina* occurs in the Paleocene *Globigerina* ooze from Hess Guyot. *Gümbelina ultimatumida* White is abundant and *G. globulosa* (Ehrenberg) is common. The third group of species occurs in the Eocene cores from Horizon Guyot. In these cores the minute Eocene forms of *Gümbelina cubensis* Palmer and *G. venezuelana* Nuttall are abundant.

Hantkenina.—*Hantkenina* Cushman, 1925, is an extinct genus with world-wide distribution in the Eocene Tethys Sea (Bronniman, 1950). The genus occurs in marls, shales, and limestones and is thought to have been a planktonic form (Thalmann, 1942b; Bronniman, 1950). The typically inflated chambers suggest a planktonic organism.

The range of the genus is noted by authors (Cushman, 1948; Glaessner, 1945) as Eocene to lower Oligocene, but Bronnimann (1950) and Thalmann (1942c) exclude the Oligocene occurrences and believe that the genus is restricted to Eocene deposits.

A species of *Hantkenina* occurs in the cores from Horizon Guyot together with other lower-middle Eocene species. This species of *Hantkenina* has spines situated in prolongation of the chamber axis which is a primitive characteristic of the genus. The species appears to be *H. mexicana* Cushman var. *aragonensis* Nuttall which is diagnostic of lower and middle Eocene. One broken specimen of *Hantkenina alabamensis* Cushman was found in the Cretaceous-Recent fauna.

Globorotalia velascoensis (*Cushman*).—This species was described by Cushman in 1925 from the Velasco shale of the Tampico Embayment area of Mexico. In the Velasco shale it is the most abundant species and is thought by Cushman (1927) to have been the dominant planktonic species of Foraminifera during Velasco time. Grimsdale (1951) states that "*Globorotalia velascoensis* is not found in the oldest layers of the Velasco formation in eastern Mexico. Nor does it reach down as far as the base of the Tertiary column in Syria." The species has been reported from the Upper Cretaceous of Mexico, Cuba, Trinidad, and Florida; and from the Paleocene and Eocene of Mexico, the Caribbean and Gulf Coast areas, and the Middle East. Muir (1936) reports this species was found in the Tampico Embayment region of Mexico with *Globotruncana arca*, the distinctive Upper Cretaceous species which died out at the end of the Maestrichtian. There is a great variation in the group of forms from which *Globorotalia velascoensis* was described and misidentifications (from the type species) are common in the literature. It appears safest, pending a close study of this form by someone having access to type material, to extend the known range from the Upper Cretaceous to the lower Eocene.

*Globorotalia velascoensis* (Cushman) appears to be a good planktonic index fossil for the Pacific area. It is found in the Mid-Pacific guyot area in the indurated ooze on Hess Guyot where it is the dominant species; and from Guyot 19171, and Horizon and Cape Johnson Guyots.

Globorotalia aragonensis *Nuttall*.—This species was described from the Aragon formation (Eocene) of Mexico and has been widely reported in the Caribbean and Gulf of Mexico areas and the Middle East. It is thus a world-wide index fossil with a geologic range reported to be lower and middle Eocene. It is very common in the Mid-Pacific guyot area and occurs on all five guyots sampled. *G. aragonensis* occurs with *G. velascoensis* in many of the *Globigerina* ooze cores which are otherwise the modern Pacific tropical planktonic fauna. In none of the pure assemblages do the two species occur together. Of all of the species of *Globigerina* and *Globorotalia* present in the fossil faunas *G. velascoensis* and, especially, *G. aragonensis* must be considered the most important and widespread in the guyot area of the Mid-Pacific Mountains.

The Cretaceous planktonic foraminiferal fauna of MP 27 is a well integrated Campanian-Maestrichtian assemblage and is very closely related to faunas of the same age from the Gulf Coast, Caribbean and adjacent areas (upper Taylor-lower Navarro, Cushman, 1946). It is a typical assemblage of the tropical to semi-tropical Tethyan Province. The range chart (fig. 4a) indicates the overlapping ranges of the species involved in this age determination. It should be noted here that because the fauna described from MP 27-2 is mixed it cannot be assumed that all of the species listed in the Upper Cretaceous faunal list existed at the same time. It is necessary here to establish a lower time range for the beginning of this mixed fauna. Overlapping ranges of the more abundant index species (*Globotruncana arca*, *G. caliciformis*, *G. contusa*, *G. fornicata*, *G. marginata*, *G. rosetta*, *G. ventricosa*, *Gümbelina costulata*, *G. plummerae*, and *G. excolata*) plus other less abundant species such as *Globotruncana gansseri* and *G. stuarti* indicate that the older elements of the mixed fauna are upper Campanian-lower Maestrichtian (upper Taylor-lower Navarro of the Gulf Coast) with a lower Maestrichtian age the most probable.

The piston-type core of MP 27 at 2050 fathoms in a basin below the slopes of Guyot 2071 has been previously noted, but the anomalous layers of gravel and the mixed Cretaceous to Recent fauna require further discussion.

Sand and gravel in deep sea deposits away from obvious sources may be due to several causes; among these are submarine slumps, landslides, mudflows, and turbidity currents. In recent years increasing attention has been paid to submarine transportation of coarse sediments and there is a growing body of literature on the subject. Turbidity currents, especially, are being studied and discussed (Turbidity currents and the transportation of coarse sediments to deep water, A Symposium, SEPM Spec. Pub. No. 2). Some of the causes for the start of a submarine landslide, slump, or mudflow which might turn into a turbidity current may be the triggering action of earthquakes, storm waves, tsunamis, tidal forces, excessive compaction rates, and deposition of slopes in excess of maximum angle of repose for the material concerned.

Kuenen (1951) favors slumping as the cause of turbidity currents in submarine canyons from slopes of 15 to 20 degrees (about those of the guyots). Menard and Ludwick (1951) believe that submarine landslides in unlithified sediments are the only likely source of dense turbidity currents thus far suggested.

In core MP 27-2 there are layers of sand and gravel separated by *Globigerina* ooze and red clay in which the constituent grains are both graded and ungraded. The bottom layer of gravel in MP 27-2 is definitely graded. Kuenen (1950) reported that graded bedding was typically the end result in his turbidity current experiments.

Slumps and landslides do not have graded bedding; this fact together with the presence of the gravel in a basin some distance away from the guyots (which are the presumed source) suggests that the sand grains, pebbles, and cobbles of basalt arrived in the basin due to transportation by turbidity current.

The conditions noted in core MP 27-2 could have occurred as follows:

(1) Erosional debris deposited on the slopes of a nearby guyot at an angle near the maximum angle of repose for the sand and gravel concerned.

(2) The start of a submarine landslide on the slopes due to triggering by some cause.

(3) The movement of the above material down slope for a long distance during which the surrounding water became mixed with the slide causing a turbidity current of high density which may have rolled large pebbles and cobbles along the bottom (as suggested by Menard and Ludwick, 1951).

(4) The arrival and deposition of this material in the basin at MP 27.

(5) The mass sliding of coarse material on the sides of the guyot could have started a series of slides and slumps which followed each other into the basin to cause the complex conditions postulated by Menard and Ludwick.

(6) At a later time other turbidity currents could have brought down coarse material from other parts of the slopes (material possibly made more unstable by the earlier removals of material) or even from other unknown guyots in the area, which formed higher layers in the bottom sediments.

The occurrence of red clay between the layers of gravel does not necessarily imply the great time intervals normally required for red clay deposition (about 1000 years per cm.). Disruption of the bottom sediments would have caused a relatively large concentration of red clay in the bottom waters in and out of the turbidity currents. This clay would fall to the bottom and form thicker layers faster than is normal.

An important point which tends to confirm the above sequence of events is the mixed Cretaceous to Recent foraminiferal fauna which is found from the top one inch to the bottom of the cores. Prior to the start of slumping or sliding there would have been a deposition of normal faunas in continuous sequence from old to young on the slopes of the guyots. If the tops and upper sides of the guyots are essentially areas of non-accumulation (discussed further below) then the result might well be a thin bed which included species of the Upper Cretaceous, Tertiary, and Recent. The Cretaceous fauna found in the gravel layers was probably at that time the planktonic fauna which was deposited with the gravel. When the submarine landslide, or slump, began to move and turned into a turbidity current, the whole mass of sediment together with its foraminiferal fauna became mixed. This mixture of Cretaceous to Recent species settled out in the basin to form the mixed fauna which was obtained in cores at MP 27.

The occurrence of restricted Upper Cretaceous species at the surface of the present sea bottom may be explained in at least two ways: (1) the sequence of events postulated above occurred quite recently and normal planktonic deposition has not buried the newly deposited material, or (2) the events occurred in the geologic past and the basin of deposition is an area of nonaccumulation due to deep currents. The configuration of the Mid-Pacific Mountains in the area in question is such that it might cause a restriction and funneling of currents through the basin, although such deep currents (at 2000 fathoms) are unknown.

The assemblage from the indurated ooze of Hess Guyot calls for further discussion. The planktonic fauna is most closely related to that from the Velasco shale of Mexico. The geologic age of the Velasco shale has been a subject of controversy for many years. Muir (1936) discussed this problem at some length and concluded together with White, Cushman, Plummer and Trager (all quoted in Muir, 1936) that the Velasco shale is uppermost Cretaceous. Nuttall (1930) thinks that the Velasco is Upper Cretaceous and Paleocene. Thalmann (1935) believed the Velasco fauna to be Paleocene as did Barker (1936) and Grimsdale (1947). Present day work in the oil fields of the Tampico Region (Salas, 1949) indicates that the Velasco formation is equivalent to the Midway (Paleocene) of the Gulf Coast Region. Noth (1951) summarizes the whole problem and concludes that "From these data we get the impression that the Velasco shales were deposited during a period which extended from the uppermost Cretaceous through the Paleocene and finally into the Eocene. It appears that the deposition of the Velasco did not start simultaneously everywhere. This might be the reason why this group is dated differently by various authors." White (personal communication, Dec. 4, 1951) stated "—Noth's comments—appear to my recollection as stating the case much to my satisfaction especially when it is remembered that I dealt only with the lower Velasco which appeared to involve transition from Cretaceous to Eocene. In those days Paleocene was a new term which in my opinion had not been properly established but whose equivalents were involved in the Velasco and thus then generally considered as Cretaceous."

The occurrence of *Eponides trümpyi* Nuttall, *Gümbelina globulosa* (Ehrenberg), *Gümbelina ultimatumida* White, common *Globigerina triloculinoides* Plummer, and *Globigerina compressa* Plummer together with a flood of *Globorotalia velascoensis* (Cushman) all argue for a Paleocene age for the indurated ooze of Hess Guyot. It is the writer's opinion that this sediment is older than the Eocene oozes on Horizon Guyot and is probably upper Paleocene (upper Midway).

Concerning the geologic history of the faunal sequences of Foraminifera, Glaessner (1945) notes that in the Caucasus, Apennines, Alps, and Pyrenees, the *Globotruncana* marls (Senonian) are followed by *Globigerina* and *Gümbelina* marls of Danian age which are in turn succeeded by Paleogene deposits rich in *Globorotalia*. Glaessner also notes this change in Mexico at the boundary of the Mendez and Velasco formations and also in Egypt, Palestine, Iraq, and Turkey. The Danian is thus a transition period before a new microfaunal cycle takes place in the Paleocene with *Globorotalia* taking the place of *Globotruncana*. Glaessner also notes that the rapid evolutionary sequence *Globorotalia velascoensis-G. aragonensis-G.* aff. *G. crassula* corresponds generally to the time interval Danian and Paleocene-lower Eocene-middle and upper Eocene. These faunal sequences as noted above by Glaessner are arguments for a Paleocene age of the indurated ooze of Hess Guyot which is dominated by *Globorotalia velascoensis*.

On Horizon Guyot, as previously noted, there is a pure unindurated fossil *Globigerina* ooze just beneath the surface although the surface species are a mixture of fossil and Recent species. This fossil ooze contains

*Globorotalia aragonensis* Nuttall, *Hantkenina mexicana* Cushman var. *aragonensis* Nuttall, *Eponides trümpyi* Nuttall, *Hastigerinella eocanica aragonensis* Nuttall, and other forms which are typical of the Aragon formation of the Tampico region of Mexico. Bermudez (1950) correlates the Aragon formation with the upper Wilcox. Salas (1949) correlates the Aragon with the lower Claiborne. The overlapping ranges of the species of the Horizon Guyot fauna together with its closeness to the Aragon fauna make an age determination of upper Wilcox-lower Claiborne about right. Expressed in broader terminology the age would be early to middle Eocene.

The sequences of foraminiferal faunas noted by Glaessner and discussed above can be recognized in the faunas of the Mid-Pacific guyots. Upper Cretaceous planktonic Foraminifera dominated by species of *Globotruncana* and *Gümbelina* were deposited among the eroded gravels on the side slopes of one of the guyots; at a later date planktonic Paleocene and Eocene Foraminifera, dominated by species of *Globorotalia* were deposited on the tops of three of the guyots. Older Foraminifera could easily be present on the tops of the guyots but their existance cannot be established because the abraded platform was not reached in any of the cores.

It should be noted that the Foraminifera, quite independently of the megafossils, date the erosion of at least one guyot as pre-Late Cretaceous (fauna in the gravel at MP 27) and the age of one of the flat tops as pre-late Cretaceous-Paleocene and the age of the flat tops of two other guyots as pre-early Eocene.

It is known that the Tethyan Province of the Cretaceous and early Tertiary was tropical to semi-tropical due to the occurrence of reef coral. The genera *Globotruncana* and *Hantkenina* apparently were confined to the Tethyan Province and adjacent areas and can thus be considered to have been Foraminifera of the then tropical to semi-tropical waters. The occurrence of these genera on the Mid-Pacific guyots affirms that the area was still covered by warm waters in the Upper Cretaceous and early Tertiary as was the situation when the reef coral-rudistid fauna grew on the tops of the ancient islands at an earlier date in the Cretaceous.

### SEDIMENTATION OF *Globigerina* OOZE ON THE GUYOTS

Most authors define *Globigerina* ooze as a sea bottom deposit containing more than 30% calcium carbonate in the form of tests of Foraminifera. The ooze is milky white, rose, yellow or brown; it is found at all depths down to about 3000 fathoms although the average maximum depth is around 2400 fathoms; *Globigerina* ooze covers approximately 47% of present day sea bottoms. (Kuenen, 1950); it is thought to be accumulating at a rate of about 1 cm. per 632 years (Shepard, 1948). The main constituents of *Globigerina* ooze are those planktonic Foraminifera which live in the pelagic realm, and plates from Coccolithophoridae. Revelle (1944) suggests the name "calcium carbonate ooze" if the material is largely fine-grained and not in the form of recognizable skeletal fragments.

*Globigerina* ooze may be absent at great depths apparently because of solution of calcium carbonate on the bottom and as the tests settle through the water column. Kuenen (1950) stresses the solvent action of cold bottom waters deficient in calcium carbonate as a reason for the absence of calcareous sediments at great depths.

The production of planktonic Foraminifera occurs in offshore water masses, especially those of the tropical and semi-tropical seas. *Globigerina* ooze accumulates where these tests are not diluted by other sediments. The occurrence of planktonic oozes in oceanic water masses is therefore no indication of deep water but rather of distance from a source of clastic sediment and/or the absence of other organisms which might mask the deposits. *Globigerina* ooze will accumulate at shallow depths, and on seamounts, and banks unless removed by waves or currents. The only implication as to depth, as far as the *Globigerina* ooze is concerned, is that the guyots were below the surface of the sea and probably below the surface zone of profuse bottom life when the Foraminifera settled to the bottom.

Shepard (1948), Ladd and Tracey (1949), and others have stated that fine sediment does not accumulate on topographic highs on the sea floor due to removal by waves and currents. The findings of MidPac reveal that this is essentially true on the Mid-Pacific guyots. Although *Globigerina* ooze was sampled on all five of the guyots studied the quantity does not appear to be commensurate with the time these bottom features have been submerged.

The top of a guyot appears to be another example of a topographic high on the sea floor which is essentially an area of non-accumulation due to the removal of fine pelagic sediments by currents. Possible evidence for this statement comes from two sources. It appears to the writer that if pelagic sediments had been allowed to pile up unhindered since the Cretaceous that the flat tops would tend to assume a conical shape; the topmost part formed of *Globigerina* ooze. Secondly, the presence of Paleocene and Eocene Foraminifera at the surface on Hess and Cape Johnson Guyots (mixed with Recent fauna) imply that ancient accumulations of *Globigerina* ooze are exposed and their submarine erosion furnishes fossil Foraminifera which are re-deposited with the slow rain of present day planktonic Foraminifera. The presence of pure, unconsolidated Eocene *Globigerina* ooze an inch or two beneath the surface of Horizon Guyot is particularly significant. These deposits of early Tertiary oozes may have accumulated initially in hollows, small erosion channels, and among the rocks. When the bank became essentially level, currents and slumping then kept the top as an area of almost no accumulation. Thus the date of fossil sediments at or near the surface may indicate the time when the bank became essentially flat, practically ceased to accumulate sediments, and planktonic forms deposited later were in large part drifted off the guyot by weak currents, aided possibly by intermittent slumping. The presence of extensive deposits of *Globigerina* ooze on the guyots indicates that there is no present-day erosion of the **basaltic** platforms (as pointed out by Kuenen, 1950).

The nine-foot core of *Globigerina* ooze taken just below the break in slope on Cape Johnson Guyot (composed of late Tertiary species with rare lower Tertiary index species) indicates that at least in places, the *Globigerina* ooze accumulates to a significant thickness. This nine-foot core may not represent normal planktonic deposition. Sediments deposited on the top of the guyot may have been swept off and have accumulated just below the break in slope where this long core was taken.

Two pictures taken on Sylvania Seamount (a guyot just northwest of Bikini Atoll) probably illustrate the typical occurrences of *Globigerina* ooze on a guyot. One shows an unbroken expanse of ooze. The other shows *Globigerina* ooze on and among manganese-coated rocks. The presence of oscillatory ripple marks in the area photographed, at a depth of 745 fathoms, indicates that deep submarine water movements exist. Menard (in press) suggests that internal waves may be a possible agent.

Indurated *Globigerina* ooze was dredged on four of the guyots. Murray and Lee (1909) record three instances (one each by the *Albatross*, *Challenger* and *Britannia*) in which hardened *Globigerina* ooze was dredged from the sea floor. On the Mid-Pacific guyots the material occurs as dry, hard, calcium carbonate ooze cemented by calcite and usually coated, at least in part, by manganese dioxide. On Hess Guyot the material was Paleocene and on Guyot 19171 it was Eocene in age. Evidence at hand is insufficient to explain the occurrence of this hardened ooze but a possible explanation might be compaction under overlying sediments, followed by reduction in water content and precipitation of calcium carbonate as a cementing material. Later removal of the unconsolidated overlying material would leave the hardened material at the surface where it could become coated with manganese dioxide.

## PLANKTONIC INDEX SPECIES OF THE PACIFIC BASIN

As a result of the discovery of the fossil planktonic assemblages on the Mid-Pacific guyots it is now possible to construct a range chart of index fossils of planktonic Foraminifera for the whole tropical and semi-tropical Pacific Basin. In view of the fact that the location of these fossil oozes was in the Middle Pacific, and the fact that they were planktonic assemblages drifted by the currents, it is a safe conclusion that

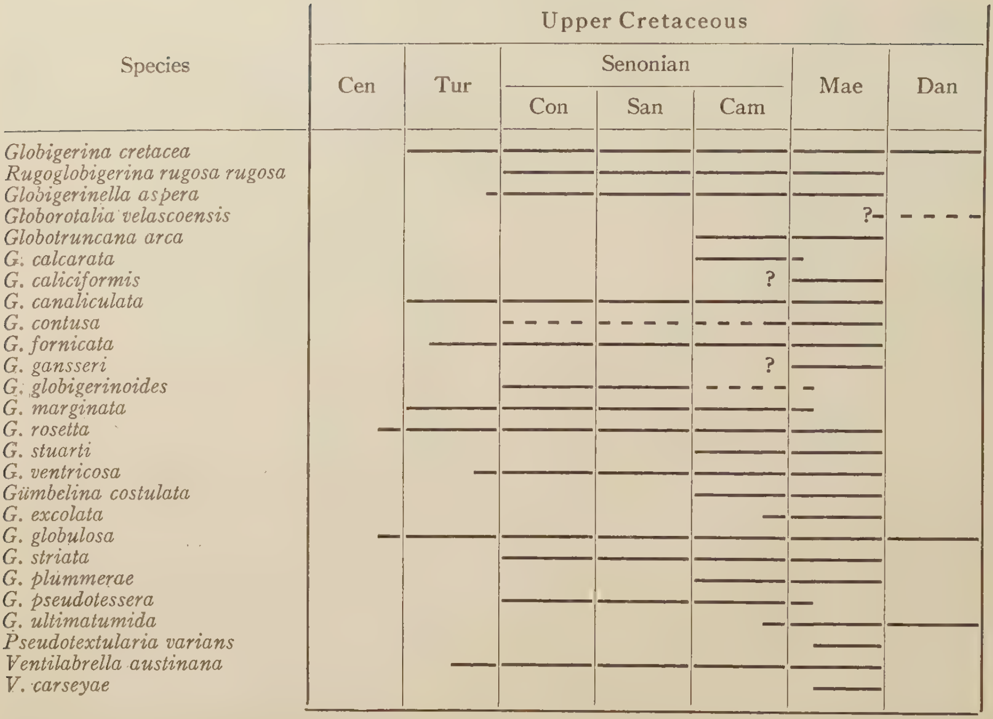

FIG. *4a*.—Upper Cretaceous planktonic index fossils from the Mid-Pacific area. World-wide ranges are indicated from referenced literature. Stages of Upper Cretaceous are: Cen: Cenomanian; Tur: Turonian; Con: Coniacian; San: Santonian; Cam: Campanian; Mae: Maestrichtian; Dan: Danian.

the fossil Foraminifera were present during their lifetime all over the tropical and semitropical Pacific Basin. This is not surprising, nor unusual, but this is the first report of the occurrence of most of these forms from the deep Pacific Ocean. Their presence could have been logically postulated and predicted, but it is satisfying to know for a fact that they were actually deposited and that they are available to date Pacific sediments and to help solve problems of sedimentation in future work.

Most of the key planktonic index fossils of the Mid-Pacific guyots are listed on the accompanying range chart (fig. 4) together with their known geologic ranges in other areas which was the basis of the age dating of this paper.

## SYSTEMATIC DESCRIPTIONS

All type material will be deposited in the U. S. National Museum, Washington, D. C.

### Family GLOBIGERINIDAE

### Genus GLOBIGERINA d'Orbigny, 1826

### GLOBIGERINA ALTISPIRA Cushman and Jarvis, 1936

Plate 30, figs. 29–30

*Globigerina altispira* CUSHMAN and JARVIS, 1936, Cushman Lab. For. Res. Contr., vol. 12, pt. 1, p. 5, pl. 1, figs. 13, 14.

This species appears to be a good index fossil of the upper Oligocene to upper Miocene. It is reported from the Miocene of Jamaica and Haiti, and from the Miocene and upper Oligocene of the Dominican Republic. Grimsdale (1951) reports this species also from the Miocene of the Middle East. This species occurs rarely in the cores from MP 27.

### GLOBIGERINA APERTURA Cushman, 1918

Plate 32, fig. 12

*Globigerina apertura* CUSHMAN, 1918, U. S. Geol. Survey Bull. 676, p. 57, pl. 12, fig. 8.

This species has been reported from the

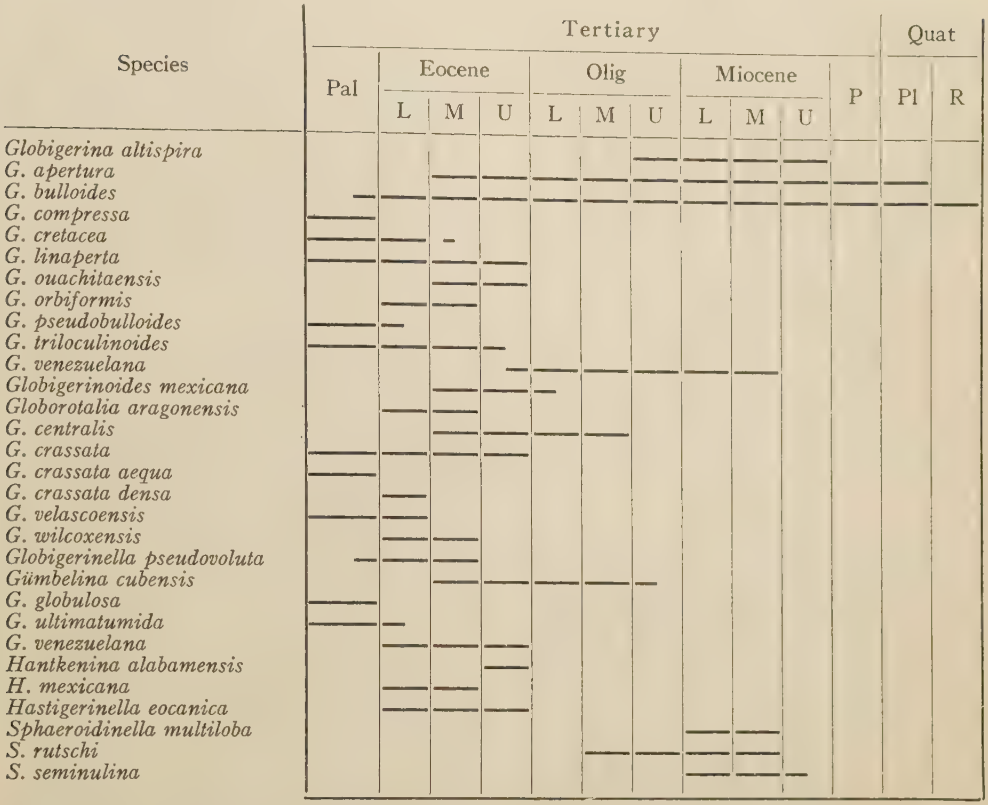

FIG. 4b.—Some of the Tertiary planktonic index fossils from the Mid-Pacific area. World-wide ranges are indicated from literature cited and the evidence of this paper.

Eocene of Mexico, the Oligocene of Cuba and Mexico, the Miocene of the Atlantic Coastal Plain, the Pliocene and Pleistocene of California. The writer has seen no reference in modern literature that this species has lived in the Recent. *G. apertura* might be a good planktonic index fossil which lived in the Pleistocene but not the Recent and would thus be a valuable form, in some cases, for differentiating the Pleistocene and Pliocene from Recent.

### GLOBIGERINA BULLOIDES d'Orbigny, 1826

Plate 30, fig. 33; plate 31, figs. 26–27; plate 32, fig. 25

*Globigerina bulloides* D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 277, no. 1; Modeles no. 76 and young, no. 17.

*Globigerina bulloides* d'Orbigny, PHLEGER and PARKER, 1951, Geol. Soc. America Mem. no. 46, p. 34, pl. 19, figs. 6, 7.

This species occurs in all of the material including Recent species. A monographic revision of the genus *Globigerina* will be necessary in order to determine the stratigraphic range of *G. bulloides*. At the present time there are scores of references ranging from the Upper Cretaceous to the Recent and including many diverse forms. Bermudez notes the range of the species from the lower Oligocene to Recent in Cuba (he includes no figures). Hornibrook (personal communication, 9 January 1952) reports that *G. bulloides* in New Zealand ranges from lower Oligocene to Recent. In material from the Mid-Pacific area *G. bulloides* d'Orbigny occurs in upper Paleocene and Eocene sediments.

### GLOBIGERINA COMPRESSA Plummer, 1926

Plate 31, figs. 14–15

*Globigerina compressa* PLUMMER, 1926, Univ. of Texas Bull., no. 2644, p. 135, pl. 8, fig. 11a–c.

This species recently reported as a world-wide index fossil (Grimsdale, 1951) is common in the upper Paleocene fauna from Hess Guyot.

### GLOBIGERINA CRETACEA d'Orbigny, 1840

Plate 31, fig. 12

*Globigerina cretacea* D'ORBIGNY, 1840, Mem. Soc. Geol. France, ser. 1, vol. 4, p. 34, pl. 3, figs. 12–14.

*Globigerina cretacea* CUSHMAN, 1931, Tennessee Geol. Bull. 41, p. 58, pl. 10, figs. 6, 7.

This species appears to be distinctive because of its flat spire on the dorsal side and ventrally the four to six inflated almost uniform chambers in the last formed whorl around the large umbilicus into which the chambers each have an aperture. The multiple aperture distinguishes this species from other similar species such as *G. pseudobulloides* Plummer, and *G. infracretacae* Glaessner.

This species has been reported from the Upper Cretaceous to the Recent, but the Cretaceous species of d'Orbigny appears to be extinct. Glaessner reports (1945, p. 206), "The typical large *Globigerina cretacea* d'Orbigny, with umbilical apertures in each of its chambers, makes its first appearance in the Turonian"; (p. 208): "—*Globigerina cretacea*,—disappear(s) suddenly at the boundary between the Senonian and Danian—". Bermudez (1950) records the species in Cuba from the Upper Cretaceous through the Paleocene and questionably to the middle Eocene. *G. cretacea* has a world-wide distribution; it is common in the cores at MP 27 and in the Paleocene indurated *Globigerina* ooze from Hess Guyot.

### GLOBIGERINA DIGITATA Brady, 1879

*Globigerina digitata* BRADY, 1879, Jour. Micr. Sci., vol. 19, p. 72; Report Voy. *Challenger*, Zool., vol. 9, p. 599, pl. 80, figs. 6–10.

This species is rare in the Recent assemblages from the Mid-Pacific Mountains area.

### GLOBIGERINA EGGERI Rhumbler, 1900

*Globigerina dubia* BRADY (not Egger), 1879, Quart. Jour. Micr. Sci., vol. 19, n.s., p. 71; 1884, Report Voy. *Challenger*, Zool., vol. 9, p. 595, pl. 79, figs. 17a–c.

*Globigerina eggeri* RHUMBLER, 1900, Nordische Plankton, pt. 14, Foraminiferen, p. 19, text figs. 20a–c.

*Globigerina eggeri* PHLEGER and PARKER, 1951, Mem. Geol. Soc. America no. 46, p. 34, pl. 19, figs. 8, 9.

This species is common in all of the Recent assemblages.

### GLOBIGERINA EOCAENA Gümbel, 1868

Plate 31, fig. 25

*Globigerina eocaena* GÜMBEL, 1868, K. Bayer. Akad. Wiss. München, Math.-Physik. Cl., Abh., München, Deutschland, Bd. 10 (1870), Abt. 2, p. 662, pl. 2, fig. 109a–b.

This species is rare in the indurated *Globigerina* ooze from Hess Guyot.

### GLOBIGERINA HEXAGONA Natland, 1938

*Globigerina hexagona* NATLAND, 1938, Bull. Scripps Inst. Ocean., Tech. Ser., vol. 4, p. 149, pl. 7, figs. 1a–c.

This planktonic species occurs rarely in the modern faunas of the Mid-Pacific area.

### GLOBIGERINA INFLATA d'Orbigny, 1839

*Globigerina inflata* D'ORBIGNY, 1839, in Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, p. 134, pl. 2, figs. 7–9.

*Globigerina inflata* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 34, pl. 19, figs. 10, 11.

This species is common in all of the Recent assemblages.

### GLOBIGERINA LINAPERTA Finlay, 1939

Plate 32, figs. 5, 6

*Globigerina linaperta* FINLAY, 1939, Trans. Roy. Soc. New Zealand, vol. 69, p. 125, pl. 13, figs. 54–57.

This New Zealand species has been reported from Egypt (Nakkady, 1950) and is common in the Eocene fauna from Horizon Guyot. Hornibrook (personal communication, 9 January 1952) reports that in New Zealand the species ranges from the Teurian to the Kaiatan (possibly Runangan)—Upper Cretaceous (upper Senonian) to upper Eocene. The distribution now established for this form makes it an important world-wide index fossil.

According to its author this species is distinguished by its slight flattening and compression of each chamber and especially by its wide but very low and hardly open aperture with a pronounced rim directed laterally to overhang a previous chamber instead of centrally.

### GLOBIGERINA MCKANNAI White, 1928

Plate 32, figs, 21, 26, 30

*Globigerina mckannai* WHITE, 1928, Jour. Paleontology, vol. 2, p. 194, pl. 27, fig. 16.

A form which appears to fall in this species is common in the Eocene cores from Horizon Guyot. *G. mckannai* was described by White from the Velasco shale of Mexico and is apparently restricted to that formation in the Tampico Embayment area.

### GLOBIGERINA ORBIFORMIS Cole, 1927
Plate 32, fig. 11

*Globigerina orbiformis* COLE, 1927, Bull. Am. Paleon., vol. 14, no. 51, p. 33, pl. 5, fig. 7.

This species is rare in the Eocene cores from Horizon Guyot. Topotype material from the National Museum was used for comparison.

### GLOBIGERINA OUACHITAENSIS Howe and Wallace, 1932
Plate 32, fig. 13

*Globigerina ouachitaensis* HOWE and WALLACE, 1932, La. Dept. Cons., Geol. Bull. 22, p. 195, pl. 10, figs. 7a–b.

This species occurs in the middle and upper Eocene of the Gulf Coast and adjacent areas. It occurs rarely in the cores at MP 27 and in the Eocene fauna from Horizon Guyot.

### GLOBIGERINA OUACHITAENSIS Howe and Wallace var. SENILIS Bandy, 1949
Plate 32, fig. 14

*Globigerina ouachitaensis* HOWE and WALLACE, 1932, La. Dept. of Cons., Geol. Bull. 22, p. 195, pl. 10, figs. 7a–b.

*Globigerina ouachitaensis* HOWE and WALLACE var. *senilis* Bandy, 1949, Bull. Am. Paleon., no. 131, p. 121, pl. 22, figs. 5a–c.

This form is rare in the Eocene cores from Horizon Guyot.

### GLOBIGERINA PSEUDOBULLOIDES Plummer, 1926
Plate 31, figs. 10–11

*Globigerina pseudobulloides* PLUMMER, 1926, Univ. of Texas Bull. No. 2644, p. 133, pl. 8, figs. 9a–c.

This species is common in the indurated *Globigerina* ooze from Hess Guyot. This species is close to *G. cretacea* d'Orbigny, but the aperture of the latter is larger and multiple and lacks the flaring lip which is a distinctive feature of *G. pseudobulloides.*

Plummer (1926) notes that this species is common in the Midway of Texas. Glaessner (1937) records the species from the Caucasus with a range from Maestrichtian (?)-Danian, Paleocene-lower Eocene (?). Nuttall (1930) records the species from the lower Eocene of Mexico.

### GLOBIGERINA QUINQUELOBA Natland, 1938

*Globigerina quinqueloba* NATLAND, 1938, Bull. Scripps Inst. Ocean., Tech. Ser., vol 4, p. 149, pl. 6, figs. 7a–c.

This species, formerly known only from the Pacific, has now been found in the Atlantic (personal communication, F. L. Parker). It is rare in the Mid-Pacific modern faunas.

### GLOBIGERINA ROTUNDATA d'Orbigny var. JACKSONENSIS Bandy, 1949
Plate 32, fig. 15

*Globigerina rotundata jacksonensis* BANDY, 1949, Bull. Am. Paleon., vol. 32, no. 131, p. 121, pl. 23, figs. 6a–c.

This form is rare in the Eocene cores from Horizon Guyot.

### GLOBIGERINA SUBCRETACEA Lomnicki, 1901
Plate 30, fig. 32

*Globigerina subcretacea* LOMNICKI, 1901, Otwornice Miocenu Pokucia, Akad. Umiejetnosci w Krakowie, Czes. II, p. 41–65; fig. Brady, Report *Challenger* Exped., vol. 9, pl. 82, fig. 10.

*Globigerina subcretacea* CHAPMAN, 1902, Jour. Linn. Soc., Zool., vol. 28, p. 410, pl. 36, figs. 16a–b (p. 404-list).

This species is distinguished from *G. eggeri* by the very flat spire on the dorsal side. It is rare in the cores from MP 27. *G. subcretacea* has been reported from the Pliocene and Pleistocene of California. It is a modern form in planktonic assemblages.

### GLOBIGERINA TRILOCULINOIDES Plummer, 1926
Plate 30, fig. 19; plate 31, fig. 13

*Globigerina triloculinoides* PLUMMER, 1926, Univ. of Texas Bull. No. 2644, p. 134, pl. 8, figs. 10 a–c.

This species is extremely widespread in sediments from the Danian to the lower Eocene; it is common in the cores from MP 27, the indurated *Globigerina* ooze from Hess Guyot and from pockets and interstices in rocks from Horizon, Hess and Cape Johnson Guyots.

### GLOBIGERINA VENEZUELANA Hedberg, 1937
Plate 30, fig. 31

*Globigerina venezuelana* HEDBERG, 1937, Jour. Paleontology, vol. 11, p. 681, pl. 92, fig. 7.

Type description: Large, nearly spherical; chambers inflated; the last three making up the bulk of the test; the early chambers form a compact spiral; wall coarsely cancellate;

aperture in a deep triangular depression between the last chambers; rare supplementary apertures are also present in some specimens. Diameter of holotype: 0.56 mm.

As figured in the original descriptions, *G. conglomerata* and *G. ouachitaensis* are not as globose as *G. venezuelana* and both appear to have four chambers of almost equal size making up the last formed whorl.

The geologic range of *G. venezuelana* is recorded from upper Eocene (Bermudez, 1950) to the middle Miocene. This species is rare in the mixed Upper Cretaceous to Recent fauna from MP 27-2.

### Genus GLOBIGERINOIDES Cushman, 1927

### GLOBIGERINOIDES CONGLOBATA (Brady), 1879

*Globigerina conglobata* BRADY, 1879, Quart. Jour. Micr. Sci., vol. 19, p. 72; Report Voy. *Challenger*, Zool., vol. 9, p. 603, pl. 80, figs. 1–5; pl. 82, fig. 5.

*Globigerinoides conglobata* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 35, pl. 19, fig. 15.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area.

### GLOBIGERINOIDES MEXICANA (Cushman), 1925

Plate 32, fig. 27

*Globigerina mexicana* CUSHMAN, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, p. 6, pl. 1, fig. 8.

This species is rare in the Eocene cores from Horizon Guyot and in the mixed Upper Cretaceous to Recent fauna from MP 27.

### GLOBIGERINOIDES NUTTALLI

Hamilton, n. sp.

Plate 32, figs. 22–24

*Globigerina* sp. NUTTALL, 1930, Jour. Paleontology, vol. 4, p. 290, pl. 24, figs. 12–15.

*Description.*—Test trochoid, calcareous, perforate, globose, almost as wide as high; chambers increasing rapidly in size; well-defined chambers typically 9–10 and arranged in three distinct whorls; the chambers of the first two four-chambered whorls globose; last chambers usually somewhat flattened and vary in size and shape; periphery distinctly lobulate between the globose chambers; wall structure, the typical hexagonal pore structure of the glo-

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EXPLANATION OF PLATE 31

Upper Paleocene fauna from Hess Guyot; from indurated *Globigerina* ooze at 915 fathoms.

FIGS. *1–4*—*Gümbelina ultimatumida* White. Four specimens; *1*, front view, of two large-chambered form, ×49; *2*, side view, ×49; *3*, front view of four large-chambered form, ×54; *4*, apertural view, ×54. (p. 235)

*5, 6*—*Gümbelina glabrans* Cushman. Two specimens; *5*, front view; *6*, side view; ×52. (p. 234)

*7, 8*—*Gümbelina* aff. *G. midwayensis* Cushman. Two specimens; *7*, front view; *8*, view of opposite side; ×52. (p. 234)

*9*—*Gümbelina globulosa* (Ehrenberg). Front view; ×52. (p. 234)

*10, 11*—*Globigerina pseudobulloides* Plummer. Two specimens; *10*, dorsal view; *11*, ventral view; ×52. (p. 223)

*12*—*Globigerina cretacea* d'Orbigny. Ventral view; ×52. (p. 222)

*13*—*Globigerina triloculinoides* Plummer. Ventral view; ×46. (p. 223)

*14, 15*—*Globigerina compressa* Plummer. Two specimens; *14*, dorsal view; *15*, ventral view; ×51. (p. 221)

*16*—*Globigerinella pseudovoluta* Bandy; ×54. (p. 226)

*17, 18*—*Globorotalia crassata* (Cushman). Two specimens; *17*, ventral view; *18*, dorsal view; ×54. (p. 229)

*19, 20*—*Globorotalia* aff. *G. angulata* (White). Two specimens; *19*, ventral view, ×62; *20*, dorsal view, ×47. (p. 229)

*21*—*Globorotalia* aff. *G. inconspicua* Howe. Ventral view; ×53. (p. 230)

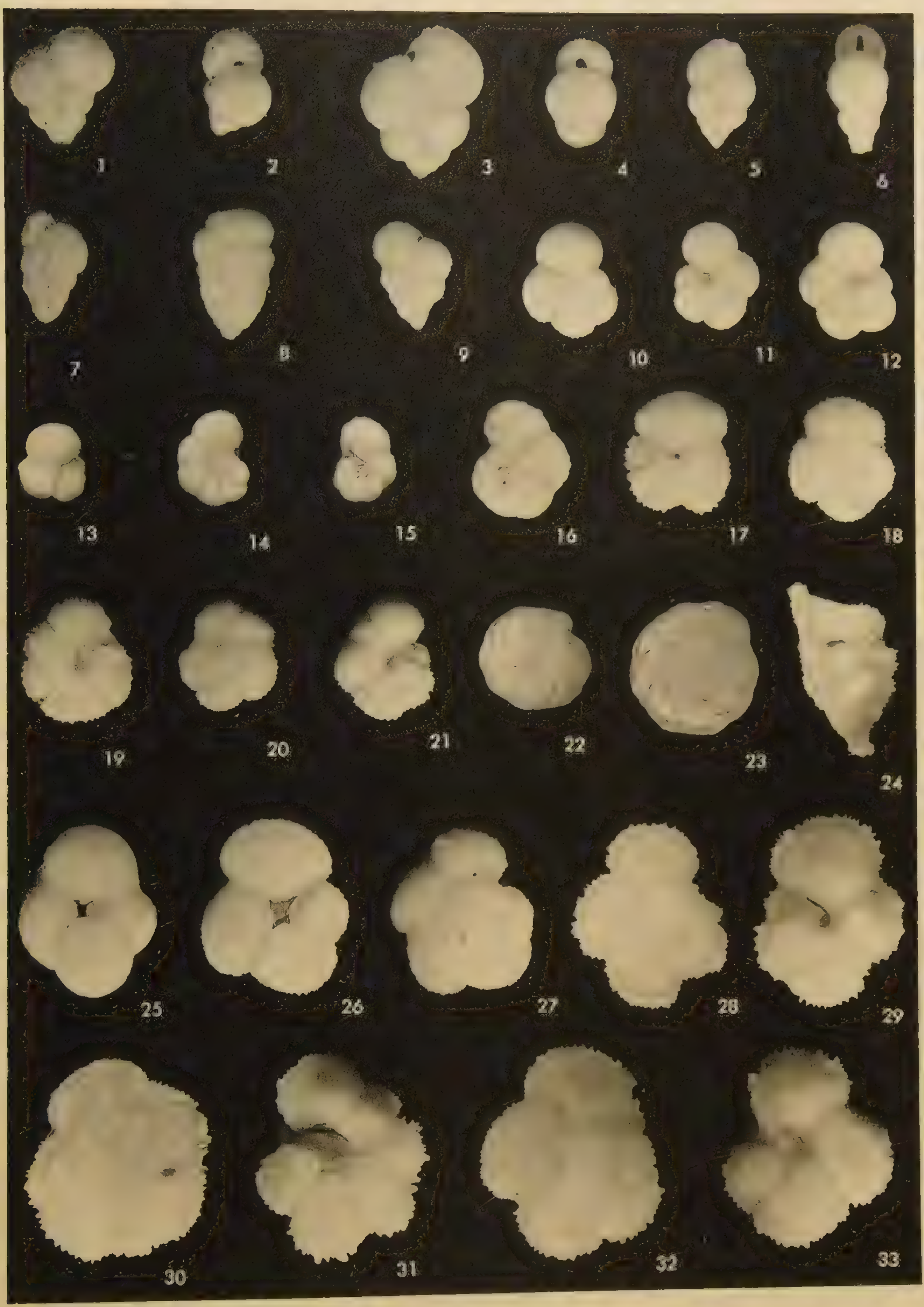
*22, 23*—*Eponides trümpyi* Nuttall. Two specimens; *22*, ventral view; *23*, dorsal view; ×53. (p. 235)

*24, 28–31*—*Globorotalia velascoensis* (Cushman). Five specimens; *24*, side view of five-chambered specimen; *28*, dorsal view; *29*, ventral view; *30*, dorsal view of six-chambered form (note beaded sutures); *31*, ventral view of six-chambered form; ×47. (p. 231)

*25*—*Globigerina eocaena* Gümbel. Ventral view; ×53. (p. 222)

*26, 27*—*Globigerina bulloides* d'Orbigny. Two specimens; *26*, ventral view, ×57; *27*, ventral view, ×54. (p. 221)

*32, 33*—*Globorotalia velascoensis* (Cushman) var. *acuta* (Toulmin) Grimsdale. Two specimens; *32*, dorsal view (note lack of beaded sutures); *33*, ventral view; ×56. (p. 231)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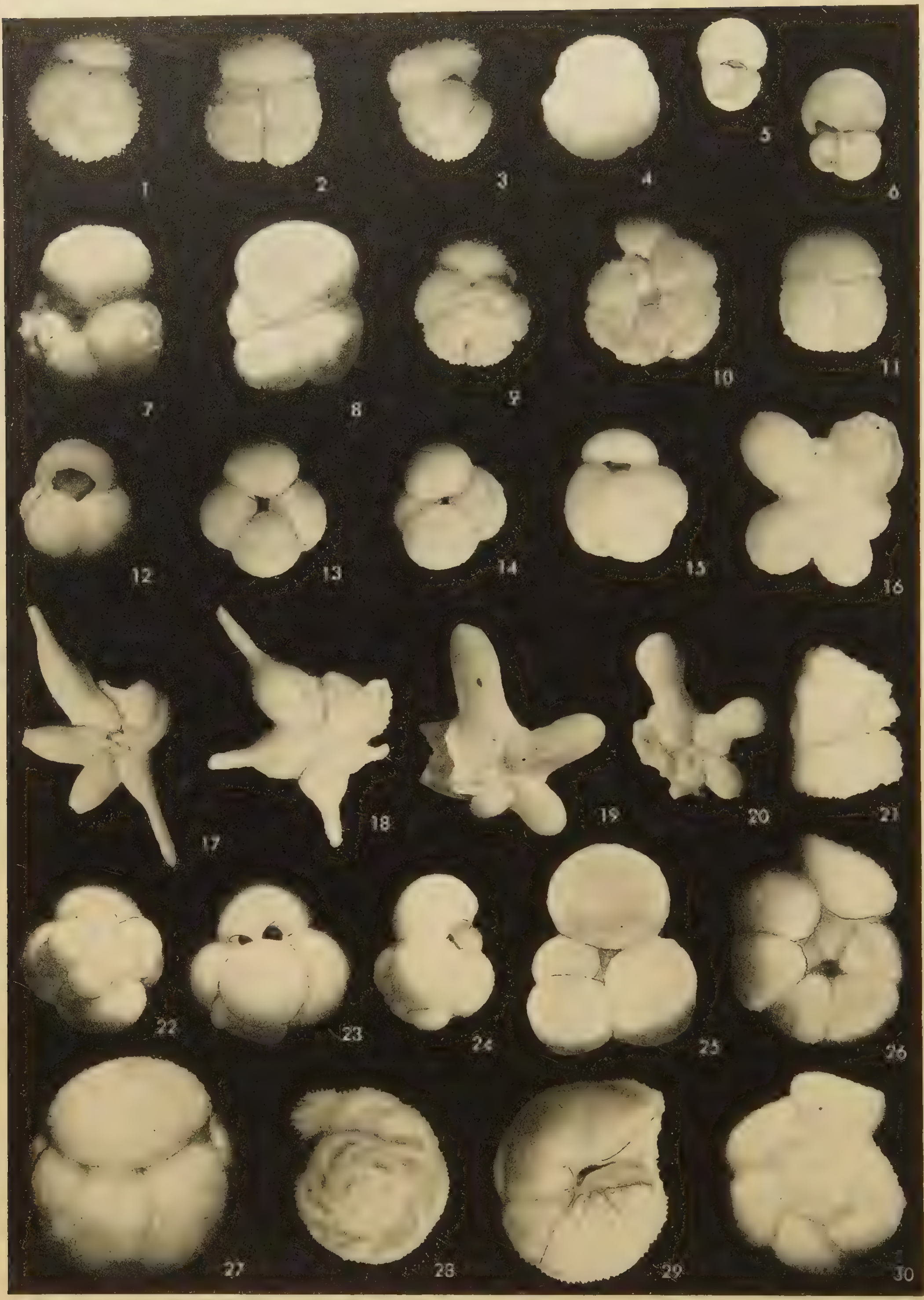
Hamilton, Foraminifera from Pacific seamounts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Hamilton, Foraminifera from Pacific seamounts

bigerinids; multiple apertures along the suture lines varying in number from one in the last chamber to two in the last chamber and one or two others into earlier chambers; apertures vary in shape from low arched openings into the last chamber to round openings into earlier chambers; some apertures have a poorly defined lip. The holotype is selected as the specimen illustrated in plate 32, fig. 23.

*Dimensions.*—Holotype: height 0.48 mm., width 0.45 mm. The holotype is about average in size. The variation in size from this average is about 0.10 mm.

*Holotype.*—Plate 32, fig. 23. Holotype to be deposited in the U. S. National Museum, Washington, D. C.

*Type Locality.*—Flat topped seamount (Horizon Guyot) at the southwest end of the volcanic ridge indicated on the U. S. Navy H. O. Chart No. 0528 at about 19°40′N. Lat. and 168°32′W. Long. This species is common in the unindurated *Globigerina* ooze taken in two Phleger cores at a depth of about 940 fathoms on the flat top of the seamount just above the break in slope between the flat top and the upper side slopes. Preservation is excellent.

*Geologic age.*—Lower Eocene.

*Discussion.*—This species was identified by the writer as *Globigerina* sp. Nuttall (1930). Nuttall's (1930) plesiotypes were obtained from the U. S. National Museum and it could be seen by comparison that these Mexican specimens had chambers which were more flattened than the Mid-Pacific specimens, but were still probably within a range of variation. The writer then sent a slide of identified specimens (including *Globigerina* sp.) to W. L. F. Nuttall in London with a request for his opinion. C. D. Ovey, to whom Nuttall referred the request, replied (personal communication, 21 March, 1952): "Your *Globigerina* sp. is identical with a *Globigerina* sp. (Registered No. P 39535) [British Museum (Natural History)] we have from the Aragon formation which, judging from Nuttall's account and figures, is the same as his *G.* sp."

*Globigerinoides nuttalli* occurs in a planktonic fauna which is very similar to the planktonic fauna of the Aragon formation of the Tampico Embayment region of Mexico (uppermost lower Eocene). *G. nuttalli* is named after Dr. W. L. F. Nuttall who first illustrated it from the Aragon formation but did not name it.

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### EXPLANATION OF PLATE 32

Eocene fauna from Horizon Guyot; unconsolidated *Globigerina* ooze from cores.

FIGS. *1–3*—*Globorotalia crassata* (Cushman). Three specimens; *1*, dorsal view; *2*, ventral view; *3*, side view; ×55. (p. 229)

*4*—*Globorotalia crassata densa* (Cushman). Ventral view; ×52. (p. 230)

*5, 6*—*Globigerina linaperta* Finlay. Two specimens; *5*, side view; *6*, ventral view; ×35. (p. 222)

*7*—*Globorotalia wilcoxensis* Cushman and Ponton. Ventral view of specimen from MP 27; ×52 (p. 231)

*8*—*Globorotalia centralis* Cushman and Bermudez. Ventral view; ×52. (p. 229)

*9, 10*—*Globorotalia* aff. *G. angulata* (White). Two specimens; *9*, dorsal view, ×51; *10*, ventral view, ×55. (p. 229)

*11*—*Globigerina orbiformis* Cole. Ventral view; ×52. (p. 223)

*12*—*Globigerina apertura* Cushman. Ventral view; ×54. (p. 220)

*13*—*Globigerina ouachitaensis* Howe and Wallace. Ventral view; ×54. (p. 223)

*14*—*Globigerina ouachitaensis* Howe and Wallace var. *senilis* Bandy. Ventral view; ×52 (p. 223)

*15*—*Globigerina rotundata* d'Orbigny var. *jacksonensis* Bandy. Ventral view; ×54. (p. 223)

*16*—*Hastigerinella eocanica* Nuttall; ×48. (p. 227)

*17, 18*—*Hantkenina mexicana* Cushman var. *aragonensis* Nuttall. Two specimens; *17*, form with extremely long chambers; ×33; *18*, ×48. (p. 229)

*19, 20*—*Hastigerinella eocanica aragonensis* Nuttall. *20*, variation with bulbous-ended chambers; ×33. (p. 227)

*21, 26, 30*—*Globigerina mckannai* White. Three specimens; *21*, side view; *26*, ventral view; *30*, dorsal view; ×53. (p. 222)

*22–24*—*Globigerinoides nuttalli* Hamilton, n. sp. Three specimens; *22*, dorsal view; *23*, side view of holotype; *24*, side view; ×52. (p. 224)

*25*—*Globigerina bulloides* d'Orbigny. Ventral view; ×53. (p. 221)

*27*—*Globigerinoides mexicana* (Cushman). Side view, ×52. (p. 224)

*28, 29*—*Globorotalia aragonensis* Nuttall. Two specimens; *28*, dorsal view; *29*, ventral view; ×47. (p. 229)

### GLOBIGERINOIDES RUBRA (d'Orbigny), 1839

*Globigerina rubra* D'ORBIGNY, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba p. 82, pl. 4, figs. 12–14.

This is the most abundant species in the Recent planktonic assemblages from the Mid-Pacific Mountains area.

### GLOBIGERINOIDES SACCULIFERA (Brady), 1877

*Globigerina sacculifera* BRADY, 1877, Geol. Mag., vol. 4, p. 535. 1884, Report Voy. *Challenger*, Zool., vol. 9, p. 604, pl. 80, figs. 11–17; pl. 82, fig. 4.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area.

### Genus GLOBIGERINITA Bronnimann, 1951

### GLOBIGERINITA GLUTINATA (Egger), 1893

*Globigerina glutinata* EGGER, 1893, Abhandl. k. bay. Akad. Wiss. Munchen, Cl. II, vol. 18, p. 371, pl. 13, figs. 19–21.

*Globigerina glutinata* RHUMBLER, 1911, Ergeb. Plankton-Exped. Humboldt Stift., vol. 3, p. 148, pl. 29, figs. 14–26; pl. 33, fig. 20; pl. 34, fig. 1.

*Globigerina glutinata* Egger has been placed in Bronnimann's genus by Miss Frances L. Parker of Scripps Institution in a manuscript based on studies of North Atlantic deep-sea cores (personal communication, September, 1951). The species is rare in the modern faunas of the Mid-Pacific area.

### Genus GLOBIGERINELLA Cushman, 1927

### GLOBIGERINELLA AEQUILATERALIS (Brady), 1879

*Globigerina aequilateralis* BRADY, 1879, Quart. Jour. Micro. Sci., vol. 19, p. 71; 1884, Report Voy. *Challenger*, Zool., vol. 9, p. 605, pl. 80, figs. 18–21.

*Globigerinella aequilateralis* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 35, pl. 19, fig. 14.

This species occurs rarely in the Recent assemblages from the Mid-Pacific Mountains area.

### GLOBIGERINELLA ASPERA (Ehrenberg), 1854

Plate 30, fig. 5

*Rotalia aspera* EHRENBERG, 1854, Mikrogeologie, Leipzig, Taf. 27, figs. 57–58; Taf. 28, figs. 42, 42a. For complete synonymy see Bandy (1951).

This species is rare in the mixed Upper Cretaceous to Recent fauna from MP 27-2.

### GLOBIGERINELLA PSEUDOVOLUTA Bandy, 1949

Plate 31, fig. 16

*Globigerinella pseudovoluta* BANDY, 1949, Bull. Am. Paleon., vol. 32, no. 131, p. 23, pl. 24, figs. 4a–b.

This species is common in the Eocene cores from Horizon Guyot and occurs rarely in the upper Paleocene fauna from Hess Guyot. Forms identified by the writer were sent to Dr. O. L. Bandy who examined them and affirmed that they were *G. pseudovoluta* Bandy. Dr. Bandy states: "Even though poorly preserved, the coarsely perforate or reticulate wall structure is discernible."

The problem of the correct taxonomic positions of *G. pseudovoluta* Bandy, *Nonion micrus* Cole, and *Nonion danvillensis* Howe and Wallace is an important one because these forms are world-wide in distribution and are important index fossils. Glaessner (1937) placed *Nonion micrus* Cole in the genus *Globigerinella* and placed *N. danvillensis* in synonymy with it. Grimsdale (1951) followed Glaessner and added *G. pseudovoluta* to the synonymy. Dr. Cole kindly sent a topotype slide of *N. micrus* to Dr. Bandy and after viewing it both Dr. Bandy and the writer believe that *N. micrus* is not the same species as *G. pseudovoluta* Bandy. Dr. Bandy (personal communication, 29 January 1952) stated: "The Cole slide has specimens that are certainly *Nonion*. Of course the perforations are conspicuous but they are fine to medium in size and they do not produce the coarsely reticulate wall structure of the globigerinoids." Dr. Bandy (personal communication, 3 January 1952) stated that in his Little Stave Creek studies (Bandy, 1949) he found that *N. danvillensis* could be differentiated from *N. micrus* by the papillate umbilical region of *N. danvillensis* (which is illustrated in the holotype figure). It would appear then that all three species are distinct. A complicating factor in the problem is that Dr. M. N. Bramlette of Scripps Institution crushed an *N. micrus* collected from the Guayabal formation of Mexico and examined it under the petrographic microscope and found that it had the radial wall structure of the globigerinids rather than the granular structure of *Nonion*. This problem deserves study by someone with a large suite of *N. micrus* Cole. At the present time the writer believes that *G. pseudovoluta* Bandy is a distinct species with world-wide distribution. The figure of *N. micrus* Cole of Glaessner (1937, Taf. 1, fig. 4 a–b) from the Eocene of the Caucasus appears to the writer to be a *G. pseudovoluta* Bandy, but lacking type material the writer is not placing it in synonymy.

### GLOBIGERINELLA VOLUTA (White), 1928

Plate 30, fig. 6

*Globigerina voluta* WHITE, 1928, Jour. Paleontology, vol. 2, p. 197, pl. 28, fig. 5.

A single specimen of this species was found in the mixed Upper Cretaceous to Recent fauna from MP 27-2. White reports it from the Velasco and Mendez formations of the Tampico Embayment area of Mexico.

## Genus RUGOGLOBIGERINA Bronnimann, 1952

### RUGOGLOBIGERINA RUGOSA RUGOSA (Plummer) Bronnimann, 1952

Plate 30, figs. 1–3

*Globigerina rugosa* PLUMMER, 1926, Univ. of Texas Bull. 2644, p. 38, pl. 2, figs. 10a–d.
*Rugoglobigerina rugosa rugosa* (Plummer) BRONNIMANN, 1952, Bull. Am. Paleon., vol. 34, no. 140, p. 28, text figs. 11–13.

Bronnimann (1952) has revised the group of Cretaceous rugose globigerinids into which this species falls and has erected the new genus *Rugoglobigerina* with Plummer's species as the genotype. This species is very close to the genus *Globotruncana* and appears to be an intermediate form between that genus and *Globigerina*. Plummer (1926) notes that the umbilical features of *Globigerina rugosa* are precisely those of *Globotruncana rosetta* (Carsey). With two peripheral keels *Rugoglobigerina rugosa* would become *Globotruncana globigerinoides* Brotzen. *R. rugosa rugosa* is common in the cores at MP 27; it has been recorded from the Navarro of Texas, the Ripley formation of Alabama, and from the Cretaceous of Trinidad.

## Genus HASTIGERINELLA Cushman, 1927

### HASTIGERINELLA EOCANICA Nuttall, 1928

Plate 32, fig. 16

*Hastigerinella eocanica* NUTTALL, 1928, Jour. Paleontology, vol. 2, p. 376, pl. 50, figs. 9–11.

This species is rare in the Eocene cores from Horizon Guyot. *H. eocanica* is established as a good index fossil with a world-wide distribution. It is reported from the Gulf of Mexico and Caribbean area, the Middle East and from the Middle Pacific; its geologic range is lower Eocene to lower Oligocene.

*H. digitata* (Rhumbler) differs from *H. eocanica* in having spines on the ends of the chambers; *H. eocanica aragonensis* Nuttall has more elongate chambers and *H. jarvisi* Cushman has chambers more elongate than *H. eocanica aragonensis* and with spines on the ends of the chambers.

### HASTIGERINELLA EOCANICA Nuttall var. ARAGONENSIS Nuttall, 1930

Plate 32, figs. 19–20

*Hastigerinella eocanica* NUTTALL, 1928, Jour. Paleontology, vol. 2, p. 376, pl. 50, figs. 9–11.
*Hastigerinella eocanica* Nuttall var. *aragonensis* NUTTALL, 1930, Jour. Paleontology, vol. 4, p. 290, pl. 24, figs. 16–17.

This variety differs from the species in having more elongate chambers. It occurs rarely in the Eocene cores from Horizon Guyot. Figure 17 of the type reference for this variety indicates that Nuttall included forms whose chambers were rounded and slightly bulbous at the ends. The form illustrated in this paper (plate 32, fig. 20) has chambers which become more bulbous at the ends as they grow larger. The writer considers this form as a variation of *H. eocanica aragonensis*. At the present time no useful stratigraphic purpose would be achieved by assigning a new varietal name.

## Genus ORBULINA d'Orbigny, 1839

### ORBULINA UNIVERSA d'Orbigny, 1839

*Orbulina universa* D'ORBIGNY, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, p. 3, pl. 1, fig. 1.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area.

The lower range of *O. universa* as a world wide index of the Tertiary is of interest

(LeRoy, 1948). It is recorded from the middle Oligocene to the Recent in the Caribbean area. Grimsdale (1951) thinks that the species is not older than the Miocene in the Gulf Coast and Caribbean area and in the Middle East. Hornibrook (personal communication, 9 January 1952) notes that the range of *O. universa* in New Zealand is from lower Miocene to Recent. Bronnimann (1951) summarizes the first appearance of the genus *Orbulina* in the Caribbean region and concludes that its first appearance is definitely in the Oligocene, but not at the same time in different localities in the Caribbean region. There appears to be valid evidence that *O. universa* first appeared in the sediments of middle to upper Oligocene age.

### Genus PULLENIATINA Cushman, 1927

### PULLENIATINA OBLIQUILOCULATA (Parker and Jones), 1865

*Pullenia obliquiloculata* PARKER and JONES, 1865, Phil. Trans., vol. 155, p. 368, pl. 19, figs. 4a–b.

*Pulleniatina obliquiloculata* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 35, pl. 19. figs. 19, 20.

This species is rare in the Recent assemblages from the Mid-Pacific Mountains area.

### Genus SPHAEROIDINELLA Cushman, 1927

### SPHAEROIDINELLA DEHISCENS (Parker and Jones), 1865

*Sphaeroidina dehiscens* PARKER and JONES, 1865, Phil. Trans., vol. 155, p. 369, pl. 19, figs. 5a–c.

*Sphaeroidinella dehiscens* SCHOTT, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. "Meteor" 1925–1927, vol. 3, pt. 3, Sect. B, p. 59.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area.

### SPHAEROIDINELLA MULTILOBA LeRoy, 1944

Plate 30, fig. 26

*Sphaeroidinella multiloba* LEROY, 1944, Colorado School Mines Quart. 39, no. 3, p. 91, pl. 4, figs. 7–9.

Forms which seem to fall into this species are rare in the mixed Upper Cretaceous to Recent fauna from MP 27-2. This form is probably a variation of *S. rutschi* Cushman and Renz. Miss Frances L. Parker has studied material from Atlantic deep-sea cores which contain lobate forms varying from *S. rutschi* and very similar, if not the same as *S. multiloba*. A large suite of *S. rutschi*, *S. multiloba* and *S. seminulina* might well reveal that the three species are variations of one species. Fortunately the three species have about the same geologic range.

### SPHAEROIDINELLA RUTSCHI Cushman and Renz, 1941

Plate 30, figs. 24–25

*Sphaeroidinella rutschi* CUSHMAN and RENZ, 1941, Cushman Lab. Foram. Res., Contr., vol. 17, p. 25, pl. 4, figs. 5a–c.

As noted by Phleger and Parker (unpublished manuscript) this species is closely related to, if not the same as, *S. seminulina* Schwager. The writer examined topotype material of specimens of *S. rutschi* and *S. seminulina* sent to Miss Frances L. Parker from the U. S. National Museum. In Miss Parker's opinion and that of the writer, the two species (in the material at hand) are the same with the possible exception that the wall of *S. seminulina* appeared to be thinner, almost translucent, and with a round pore structure which appeared as white dots, whereas *S. rutschi* had the typical hexagonal pore structure of the Globigerinidae, and a thicker, whiter wall. This problem should be studied by someone with a large number of topotype specimens of both species. Fortunately the two species are reported to have about the same geologic range: *S. seminulina* from the upper Oligocene to the lower Pliocene and *S. rutschi* from the middle Oligocene to the middle Miocene.

### SPHAEROIDINELLA SEMINULINA (Schwager), 1866

Plate 30, figs. 27–28

*Globigerina seminulina* SCHWAGER, 1866, Novara. Exped., Geol. Theil, vol. 2, p. 256, pl. 7, fig. 112.

*Sphaeroidinella seminulina* BERMUDEZ, 1949, Cushman Lab. Foram. Res., Sp. Publ. 25, p. 283, pl. 21, fig. 59.

This species differs from *S. dehiscens* in its smaller size and by the lack of an aperture on the dorsal side. *S. seminulina* occurs rarely in the cores from MP 27.

For further remarks see note under *S. rutschi*.

### Genus CANDEINA d'Orbigny

### CANDEINA NITIDA d'Orbigny, 1839

*Candeina nitida* D'ORBIGNY, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, p. 108, pl. 2, figs. 27, 28.

*Candeina nitida* BRADY, 1884, Report *Challenger*, Zool., vol. 9, p. 622, pl. 82, figs. 13–20.

This species is rare in the Recent assemblages from the Mid-Pacific Mountains area.

### Family HANTKENINIDAE

### Genus HANTKENINA Cushman, 1924

### HANTKENINA ALABAMENSIS Cushman, 1924

Plate 30, fig. 20

*Hantkenina alabamensis* CUSHMAN, 1924, Proc. U. S. Nat. Mus., vol. 66, art. 30, p. 3, pl. 1, figs. 1–6; pl. 2, fig. 5.

One broken specimen of this species was found in the mixed Upper Cretaceous to Recent fauna from MP 27-2.

### HANTKENINA MEXICANA Cushman var. ARAGONENSIS Nuttall, 1930

Plate 32, figs. 17, 18

*Hantkenina mexicana* CUSHMAN, 1924, Proc. U. S. Nat. Mus., vol. 66, art. 30, p. 3, pl. 2, fig. 2.

*Hantkenina mexicana* Cushman var. *aragonensis* NUTTALL, 1930, Jour. Paleontology, vol. 4, p. 284, pl. 24, figs. 1–3.

This variety differs from the type in having larger more inflated chambers which always taper more gradually into the terminal spines. Thalmann (1942b) elevated this variety to specific rank, but Bronnimann (1950) stated that: "In the present material it was difficult to distinguish consistently between them (*H. mexicana* and *H. mexicana aragonensis*-writer's note) and therefore it is considered that the two forms are the extreme variants of a single species, connected by transitional forms."

### Family GLOBOROTALIIDAE

### Genus GLOBOROTALIA Cushman, 1927

### GLOBOROTALIA aff. G. ANGULATA (White), 1928

Plate 31, figs. 19, 20; plate 32, figs. 9, 10

*Globigerina angulata* WHITE, 1928, Jour. Paleontology, vol. 2, p. 191, pl. 27, fig. 13a–c.

*Globorotalia angulata* (White) GLAESSNER, 1937, Publ. Paleon. Lab. Moscow Univ., Problems in Paleontology, II–III, p. 383, pl. 4, figs. 35a–c; 36a–c; 37a–c.

Forms which are close to *G. angulata* White, but with a more rounded periphery, are rare in the upper Paleocene fauna from Hess Guyot.

### GLOBOROTALIA ARAGONENSIS Nuttall, 1930

Plate 32, figs. 28, 29

*Globorotalia aragonensis* NUTTALL, 1930, Jour. Paleontology, vol. 4, p. 288, pl. 24, figs. 6–8, 10, 11.

This species first reported from the Aragon formation of Mexico is a world-wide index fossil for the lower and middle Eocene. It is reported from the Middle East, the Gulf Coast and Caribbean area and now from the Mid-Pacific. *G. aragonensis* is abundant in cores from the top of Horizon Guyot, is common in the indurated *Globigerina* ooze boulder from Guyot 19171, and the cores at MP 27.

### GLOBOROTALIA CENTRALIS Cushman and Bermudez, 1937

Plate 32, fig. 8

*Globorotalia centralis* CUSHMAN and BERMUDEZ, 1937, Contr. Cushman Lab. Foram. Res., vol. 13, p. 26, pl. 2, figs. 62–65.

This form is common in the Eocene cores from Horizon Guyot.

### GLOBOROTALIA CRASSATA (Cushman), 1925

Plate 31, figs. 17, 18; plate 32, figs. 1–3

*Pulvinulina crassata* CUSHMAN, 1925, Bull., Am. Assoc. Pet. Geol., vol. 9, p. 300, pl. 7, fig. 4.

*Globorotalia crassata* COLE, 1927, Bull. Amer. Paleont., vol. 14, no. 51, p. 34, pl. 1, figs. 7–8.

*Globorotalia crassata* (CUSHMAN), 1939, Contr. Cushman Lab. Foram. Res., vol. 15, p. 74, pl. 12, fig. 19.

Plesiotype material of the last-named citation above was obtained from the National Museum and compared with the material from the Mid-Pacific area. This species is common in the mixed Upper Cretaceous to Recent fauna from MP 27-2 and occurs in the upper Paleocene fauna from Hess Guyot, and is abundant in the Eocene fauna from the cores from Horizon Guyot. It also occurs in the mixed faunas from all five guyots as well as in the Eocene fauna of Guyot 19171.

### GLOBOROTALIA CRASSATA (Cushman) var. AEQUA Cushman and Renz, 1942
Plate 30, figs. 21, 22

*Pulvinulina crassata* CUSHMAN, 1925, Bull., Am. Assoc. Pet. Geol., vol. 9, p. 300, pl. 7, fig. 4.

*Globorotalia crassata aequa* CUSHMAN and RENZ, 1942, Contr. Cushman Lab. Foram. Res., vol. 18, p. 12, pl. 3, fig. 3.

The variety differs from the species in the much smoother surface, and in that the chambers, especially the later ones, are broader and more arcuate. The variety differs from *G. wilcoxensis* in that the periphery is bluntly angular and unkeeled, and the aperture is elongate.

This variety occurs rarely in the cores from MP 27. It is apparently confined to the Paleocene.

### GLOBOROTALIA CRASSATA DENSA (Cushman), 1939
Plate 32, fig. 4

*Pulvinulina crassata densa* CUSHMAN, 1925, Bull., Am. Assoc. Pet. Geol., vol. 9, p. 301, no figure.

*Globorotalia crassata densa* (CUSHMAN), 1939, Contr. Cushman Lab. Foram. Res., vol. 15, p. 74, pl. 12, fig. 20.

Plesiotype material of the last named citation was obtained from the National Museum and compared with the forms from the Mid-Pacific area. This variety is common in the Eocene fauna from Horizon Guyot and in the mixed fauna of MP 27-2.

### GLOBOROTALIA HIRSUTA (d'Orbigny), 1839

*Rotalina hirsuta* D'ORBIGNY, 1839, in Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, Foraminiferes, p. 131, pl. 1, figs. 37–39.

*Pulvinulina canariensis* BRADY (not d'Orbigny), 1884, Report Voy. *Challenger*, Zool., vol. 9, p. 692, pl. 103, figs. 8–10.

*Globorotalia hirsuta* CUSHMAN, 1931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 99, pl. 17, figs. 6a–c.

This species occurs rarely in the modern faunas of the Mid-Pacific area.

### GLOBOROTALIA aff. G. INCONSPICUA Howe, 1939
Plate 31, fig. 21

*Globorotalia inconspicua* HOWE, 1939, La. Dept. of Cons. Geol. Bull. 14, p. 85, pl. 12, fig. 20–22.

Forms close to *G. inconspicua* Howe, but with a more rounded periphery, are rare in in the upper Paleocene fauna from Hess Guyot and common in the Eocene cores from Horizon Guyot.

### GLOBOROTALIA MENARDII (d'Orbigny), 1826

*Rotalia menardii* D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 273, no. 26; Modeles no. 10.

*Pulvinulina menardii* BRADY, 1884, Report Voy. *Challenger*, Zool., vol. 9, p. 690, pl. 103, figs. 1, 2.

*Globorotalia menardii* CUSHMAN, 1931, Bull. U. S. Nat. Mus. no. 104, pt. 8, p. 91, pl. 17, figs. 1a–c.

*Globorotalia menardii* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. no. 46, p. 36, pl. 20, figs. 1, 2.

This species is common to rare in all Recent assemblages from the Mid-Pacific Mountain area. It occurs widely in sediments from the lower Miocene to the Recent. Galloway and Heminway (1941) record *G. menardii* from the lower Oligocene of Porto Rico.

### GLOBOROTALIA PUNCTULATA (d'Orbigny), 1826

*Globigerina punctulata* D'ORBIGNY, 1826, Ann. Sci. Nat., vol. 7, p. 277, no. 8.

*Globorotalia punctulata* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, pl. 20, figs. 3–7.

This species is rare in the Recent assemblages of the Mid-Pacific area.

### GLOBOROTALIA SCITULA (Brady), 1882

*Pulvinulina scitula* BRADY, 1882, Proc. Roy. Soc. Edinburgh, vol. 11, p. 716; BALKWILL and MILLET, Jour. Micro., vol. 3, p. 85, pl. 4, fig. 12, 1884.

*Globorotalia scitula* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 36, pl. 20, figs. 8, 9.

This species is rare in the Recent assemblages from the Mid-Pacific area.

### GLOBOROTALIA TRUNCATULINOIDES (d'Orbigny), 1839

*Rotalina truncatulinoides* D'ORBIGNY, 1839, in Barker-Webb and Berthelot, Hist. Nat. Iles Canaries, vol. 2, pt. 2, p. 132, pl. 2, figs. 25–27.

*Globorotalia truncatulinoides* PHLEGER and PARKER, 1951, Geol. Soc. America Mem. 46, p. 36, pl. 20, figs. 10–13.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area. Grimsdale (1951) records the species from the upper Miocene to Recent in the Gulf of Mexico and Caribbean areas.

### GLOBOROTALIA TUMIDA (Brady), 1877

*Pulvinulina menardii* d'Orbigny var. *tumida* BRADY, 1877, Geol. Mag., vol. 4, p. 294.

*Pulvinulina tumida* BRADY, 1884, Report *Challenger* Zool., vol. 9, p. 692, pl. 103, figs. 4–6.

*Globorotalia tumida* Phleger and Parker, 1951, Geol. Soc. America Mem. 46, p. 36, pl. 20, figs. 14, 15.

This species is common in the Recent assemblages from the Mid-Pacific Mountains area.

### GLOBOROTALIA VELASCOENSIS (Cushman), 1925

Plate 30, figs. 16–18, 23; plate 31, figs. 24, 28–31

*Pulvinulina velascoensis* Cushman, 1925, Cushman Lab. Foram. Res., Contr., vol. 1, p. 19, pl. 3, figs. 5a–c.
*Globorotalia velascoensis* (Cushman) Cushman, 1927, Jour. Paleontology, vol. 1, pl. 27, figs. 7–9.
*Globorotalia velascoensis* White, 1928, Jour. Paleontology, vol. 2, p. 281, pl. 38, figs. 2a–c.
*Globorotalia aragonensis* Nuttall var. *caucasica* Glaessner, 1937, Publ. Paleon. Lab. Moscow Univ., Studies in Micropaleontology, vol. 1, fasc. 1, p. 31, figs. 6a–c.

This species is an outstanding index fossil with a world-wide distribution. It is the most abundant species in the Velasco shale of the Tampico Embayment region of Mexico, and has been noted from Cuba, Trinidad, Florida, Egypt and the Middle East. The specimens from the Mid-Pacific area are extremely well preserved and abundant. It is the dominant species in the indurated *Globigerina* ooze from Hess Guyot and is found on Horizon and Cape Johnson Guyots and from the cores at MP 27.

In view of its importance as an index fossil the geologic range of *G. velascoensis* assumes some importance. Grimsdale (1947 and 1951) records the form as upper Paleocene to lower Eocene in the Gulf of Mexico and Caribbean areas and from the upper Paleocene to middle Eocene in the Middle East. He (1951) specifically states that the form is not found in the lower part of the Velasco shale in Mexico. Cushman (1927) states that *G. velascoensis* is common in the lower and middle Velasco. Bermudez (1950) records the form from the Upper Cretaceous Habana formation of Cuba. Cushman and Bermudez (1949) also record the species from the Cuban Cretaceous. Nakkady (1950) records *G. velascoensis* from the Cretaceous-Paleocene Esna shales of Egypt. Part of the controversy concerns the age of the Velasco shale of Mexico, which is thought to be, at least in part, Cretaceous by many authors. Dorr (in Muir, 1936) states that *G. velascoensis* occurs with *Globotruncana arca* in the Tampico Embayment region and that the forms were indigenous. In summation the geologic range of *G. velascoensis* is questionably Upper Cretaceous and definitely Paleocene and lower to middle Eocene.

### GLOBOROTALIA VELASCOENSIS (Cushman) var. ACUTA (Toulmin), 1941

Plate 31, figs. 32–33

*Globorotalia wilcoxensis* Cushman and Ponton var. *acuta* Toulmin, 1941, Jour. Paleontology, vol. 15, p. 608, pl. 82, figs. 6–8.
*Globorotalia velascoensis* (Cushman) var. *acuta* (Toulmin) Grimsdale, 1951, Proc. Third Pet. Congress, Section 1, Preprint 7, p. 9.

The writer agrees with Grimsdale that this variety is much closer to the species *G. velascoensis* than it is to *G. wilcoxensis*. The variety occurs commonly with *G. velascoensis* in the indurated *Globigerina* ooze from Hess Guyot and on Horizon Guyot and in the cores from MP 27. It is separated from *G. velascoensis* only by the fact that its sutures are not beaded. The geologic range of the variety is noted by authors to be Paleocene to middle Eocene.

### GLOBOROTALIA WILCOXENSIS Cushman and Ponton, 1932

Plate 32, fig. 7

*Globorotalia wilcoxensis* Cushman and Ponton, 1932, Cushman Lab. Foram. Res., Contr., vol. 8, p. 71, pl. 9, fig. 10.

This species is rare in the cores from MP 27. The geologic range of the species is Paleocene to middle Eocene. Type material from the U. S. National Museum was compared with the Mid-Pacific material.

### Genus GLOBOTRUNCANA Cushman, 1927

### GLOBOTRUNCANA ARCA (Cushman), 1926

Plate 29, figs. 1–3

*Pulvinulina arca* Cushman, 1926, Cushman Lab. Foram. Res. Contr., vol. 2, pt. 1, p. 23, pl. 3, figs. 1 a–c.
*Globotruncana arca* (Cushman), 1927, Cushman Lab. Foram. Res., Contr., vol. 3, p. 91, pl. 19, fig. 11.
*Globotruncana arca* (Cushman) Bandy, 1951, Jour. Paleontology, vol. 25, p. 509, pl. 75, figs. 1a–c.

This distinctive biconvex, double-keeled species ranges from the Campanian to the end of the Maestrichtian in the Caucasus and is found in the Taylor and Navarro sediments of the Gulf Coast and adjacent areas. It is common in the cores at MP 27.

### GLOBOTRUNCANA CALCARATA Cushman, 1927
Plate 29, figs. 4, 5

*Globotruncana calcarata* CUSHMAN, 1927, Contr. Cushman Lab. Foram. Res., vol. 3, p. 115, pl. 23, fig. 10a–b.
*Globotruncana calcarata* CUSHMAN, 1946, U. S. Geol. Survey Prof. Paper 206, p. 151, pl. 62, fig. 8.

A single specimen of this distinctively spined species was found in the mixed Upper Cretaceous to Recent fauna from MP 27-2.

### GLOBOTRUNCANA CALICIFORMIS (de Lapparent), 1918
Plate 29, figs. 6–8

*Rosalina linnei* mutation *caliciforme* DE LAPPARENT, 1918, Carte geol. France Mem., p. 8, fig. 2j, pl. 1, fig. 2.
*Globotruncana caliciformis* (de Lapparent) CITA, 1948, Riv. italiana paleontologia anno 54, fasc. 4, p. 148–149, pl. 3, figs. 4a–c.
*Globotruncana caliciformis* (de Lapparent) BOLLI, 1951, Jour. Paleontology, vol. 25, p. 194, pl. 34, figs. 4–6.

This species is common in the mixed Upper Cretaceous to Recent fauna of MP 27-2. An identified specimen was sent to Dr. Hans Bolli in Trinidad who stated (personal communication, 23 February 1952) that it was conspecific with his Trinidad form.

### GLOBOTRUNCANA CANALICULATA (Reuss), 1854
Plate 29, figs. 9, 10

*Rosalina canaliculata* REUSS, 1854, Akad. Wiss. Wien., Math.-naturwiss. Kl., Denkschr., vol. 7, pt. 1, p. 70, pl. 26, fig. 4.
*Globotruncana canaliculata* CUSHMAN, 1946, U. S. Geol. Survey Prof. Paper 206, p. 149, pl. 61, figs. 17 and 18.
*Globotruncana canaliculata* BANDY, 1951, Jour. Paleontology, vol. 25, p. 509, pl. 75, figs. 2a–c.

Forms which have nearly parallel sides and are double-keeled are usually placed in this species in American literature. There is a suspicion, however, that *G. canaliculata* and *G. linnei* (d'Orbigny) are the same (Glaessner, 1937; Bolli, 1951). As pointed out by Bolli (1951) a monographic revision will be necessary to solve some of these questions. This species is rare in the cores at MP 27.

### GLOBOTRUNCANA CONTUSA (Cushman), 1946
Plate 29, figs. 14–16

*Globotruncana arca* var. *contusa* CUSHMAN, 1946, U. S. Geol. Survey Prof. Paper 206, p. 150–151, pl. 62, figs. 6a–b.
*Globotruncana contusa* (Cushman) CITA, 1948, Riv. italiana paleontologia, anno 54, fasc. 4, pp. 150–151, pl. 3, figs. 5a–c.
*Globotruncana contusa* (Cushman) BOLLI, 1951, Jour. Paleontology, vol. 25, p. 196, pl. 34, figs. 7–9.

This species is common in the mixed Upper Cretaceous to Recent fauna from MP 27-2. An identified specimen was sent to Dr. Hans Bolli in Trinidad who agreed that the form was conspecific with his Trinidad species.

### GLOBOTRUNCANA FORNICATA Plummer, 1931
Plate 29, fig. 21

*Globotruncana fornicata* PLUMMER, 1931, Univ. Texas Bull. 3101, p. 198, pl. 13, figs. 4–6.
*Globotruncana fornicata* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 149, pl. 61, fig. 19.

This biconvex, double-keeled species differs from *G. arca* in having strongly curved sutures on the dorsal side which give the chambers on that side a distinctive "sausage-shaped" appearance. The species is common in the cores at MP 27. This species is reported in the Taylor and Navarro sediments of the Gulf Coast and adjacent areas and from the Emscher to the Campanian in the Caucasus.

### GLOBOTRUNCANA GANSSERI Bolli, 1951
Plate 29, figs. 18–20

*Globotruncana gansseri* BOLLI, 1951, Jour. Paleontology, vol. 25, p. 196, pl. 35, figs. 1–3.

This species is common in the mixed Upper Cretaceous to Recent fauna of MP 27-2. An identified specimen was sent to Dr. Hans Bolli in Trinidad who agreed (personal communication, 23 February 1952) that it was *G. gansseri*. He further stated that he had found *G. gansseri* in Upper Cretaceous Cuban material.

### GLOBOTRUNCANA GLOBIGERINOIDES
### Brotzen, 1936
Plate 29, figs. 17, 22

*Globotruncana globigerinoides* BROTZEN, 1936, Sveriges geol. Undersokning, ser. C, no. 396, Arsbok 30, no. 3, pl. 12, figs. 3a–c, pl. 13, fig. 3.
*Globotruncana globigerinoides* Brotzen, BOLLI, 1951, Jour. Paleontology, vol. 25, p. 198, pl. 35, figs. 16–18.

This species differs from species of *Globigerina* in having a faint double keel around the periphery of the globose chambers; it is especially close to *Globigerina rugosa* Plummer reported from the Navarro of Texas. The range of the species is reported by Glaessner (1937) as Coniacian-Santonian, but its occurrence in the cores at MP 27, together with distinctive species such as *G. arca* and *G. fornicata*, extend its range upward into the Campanian and Maestrichtian.

### GLOBOTRUNCANA MARGINATA
### (Reuss), 1845
Plate 29, figs. 23–25

*Rosalina marginata* REUSS, 1845, Verstein. bohm., Kreideformation, pt. 1, p. 36, pl. 8, figs. 54, 74; pl. 13, figs. 6–8.
*Globotruncana marginata* THALMANN, 1934, Eclogae geol. Helvetiae, vol. 27, p. 414.
*Globotruncana marginata* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 150, pl. 62, figs. 1, 2.

This flat to biconvex, double-keeled species is distinguished by its inflated, globigerinid chambers. This species is reported from the Eagle Ford to the lower Navarro in the Gulf Coast and adjacent areas and from the Turonian-Santonian to Campanian in the Caucasus. Bolli (1951) places the form reported by Cushman (1946) in the *G. lapparenti bulloides* Vogler group and notes that this group is found in Trinidad from the Turonian to Maestrichtian. This species is common in the cores from MP 27.

### GLOBOTRUNCANA ROSETTA
### (Carsey), 1926
Plate 29, figs. 26–28

*Globigerina rosetta* CARSEY, 1926, Univ. Texas Bull. 2612, p. 44, pl. 5, figs. 3a–c.
*Globotruncana rosetta* WHITE, 1928, Jour. Paleontology, vol. 2, p. 286, pl. 39, fig. 1.

There is confusion between this species reported by authors from the American Cretaceous section and *G. stuarti* (de Lapparent). Two recent papers illustrate this confusion. Bolli (1951) places Cushman's figure 5 (1946, pl. 62, fig. 5) in *G. stuarti* and Bandy (1951) places the same figure in *G. rosetta.* Glaessner (1937, p. 41) probably illustrates the difference between these two species: *G. stuarti* is single-keeled and distinctly conical on the dorsal side; *G. rosetta* is flat to slightly convex on the dorsal side and is also single-keeled. To add to the confusion some authors include single-keeled forms similar to *G. stuarti* and *G. rosetta* in *G. arca.* For the present the writer is placing those forms with flat to "slightly" convex dorsal sides in the species *G. rosetta.*

### GLOBOTRUNCANA STUARTI (de
### Lapparent), 1918
Plate 29, figs. 11–13

*Rosalina stuarti* DE LAPPARENT, 1918, Carte geol. France Mem., p. 12, fig. 4, p. 13, fig. 5.
*Globotruncana stuarti* (de Lapparent) RENZ, 1936, Eclogae geol. Helvetiae, vol. 29, no. 1, p. 19, pl. 6, figs. 35–41; pl. 8, fig. 6.
*Globotruncana stuarti* (de Lapparent) GLAESSNER, 1937, Publ. Lab. Paleon. Moscow Univ., Studies in Micropaleontology, vol. 1, fasc. 1, p. 39, Taf. 1, figs. 14a–c.
*Globotruncana stuarti* (de Lapparent), BOLLI, 1951, Jour. Paleontology, vol. 25, p. 196, pl. 34, figs. 10–12.

This species is rare in the mixed Upper Cretaceous to Recent fauna from MP 27-2. See remarks under *Globotruncana rosetta* (Carsey).

### GLOBOTRUNCANA VENTRICOSA
### (White), 1928
Plate 29, figs. 29–31

*Globotruncana canaliculata ventricosa* WHITE, 1928, Jour. Paleontology, vol. 2, p. 284, pl. 38, fig. 5.
*Globotruncana ventricosa* BROTZEN, 1936, Sveriges geol. Undersokning, ser. C, no. 396, p. 171, pl. 13, figs. 4a–c, text fig. 63.
*Globotruncana ventricosa* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 150, pl. 62, fig. 3. (copy of White's figure).

This species is distinguished by its flat dorsal side, double keel, and highly convex ventral side; it is common in the cores from MP 27. This species is reported from the Campanian of the Gulf Coast and adjacent regions, the Campanian and Maestrichtian of Trinidad and from the Coniacian to the Maestrichtian in the European section.

### Family HETEROHELICIDAE

### Genus GÜMBELINA Egger, 1899

### GÜMBELINA COSTULATA Cushman, 1938
Plate 30, fig. 12

*Gümbelina costulata* CUSHMAN, 1938, Cushman Lab. Foram. Res., Contr., vol. 14, p. 16, pl. 3, figs. 7–9.

*Gümbelina costulata* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 108, pl. 46, figs. 10-12.

This costate species appears to be confined to the Campanian and Maestrichtian. It is common in the cores at MP 27.

### GÜMBELINA CUBENSIS Palmer, 1934

*Gümbelina cubensis* PALMER, 1934, Mem. Soc. Cubana Hist. Nat., vol. 8, p. 74, text figs. 1–6.

This species is common in the cores on Horizon Guyot. Its geologic range in the Gulf of Mexico-Caribbean area is upper Eocene to upper Oligocene. It is interesting to note that this range extends the range of the genus *Gümbelina* to the upper Oligocene.

### GÜMBELINA EXCOLATA Cushman, 1926
Plate 30, fig. 11

*Gümbelina excolata* CUSHMAN, 1926, Contr. Cushman Lab. Foram. Res., vol. 2, p. 20, pl. 2, fig. 9.

This species is rare in the mixed Upper Cretaceous to Recent fauna from MP 27-2. It is a larger and more coarsely ornamented form than *G. costulata*.

### GÜMBELINA GLABRANS Cushman, 1938
Plate 31, figs. 5, 6

*Gümbelina glabrans* CUSHMAN, 1938, Cushman Lab. Foram. Res., Contr., vol. 14, p. 15, pl. 3, figs. 1, 2.

*Gümbelina glabrans* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 109, pl. 46, figs. 17, 18.

This species is rare in the indurated *Globigerina* ooze from Hess Guyot. It appears to be confined to rocks of Navarro age in the Gulf Coast area, but ranges from the Campanian to the Maestrichtian in the Pyrenees.

### GÜMBELINA GLOBULOSA (Ehrenberg), 1854
Plate 30, fig. 15; plate 31, fig. 9

*Textilaria globulosa* EHRENBERG, 1854, K. preuss. Akad. Wiss. Berlin, Abh., p. 135, pl. 4, fig. 4b, 1834; Mikrogeologie, pl. 21, fig. 87.

*Gümbelina globulosa* EGGER, 1899, K. bayer. Akad. Wiss., Math.-naturh., Abt., Abh. Kl. 2, vol. 21, pt. 1, p. 32, pl. 14, fig. 43.

*Gümbelina globulosa* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 105, pl. 45, figs. 9–15. (for complete synonymy see this paper).

This species is common in the Gulf Coast and adjacent regions in the Campanian and Maestrichtian. It is reported in the Pyrenees from the Coniacian to the end of the Danian and from the Midway of Mexico. It is common in the cores at MP 27 and from the sediments on Hess Guyot.

### GÜMBELINA PLUMMERAE Loetterle, 1937
Plate 30, fig. 10

*Gümbelina plummerae* LOETTERLE, 1937, Nebraska Geol. Surv. Bull., 2nd ser., Bull. 12, p. 33, pl. 5, figs. 1, 2.

*Gümbelina plummerae* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 104, pl. 45, figs. 1–3.

This species is widely distributed in the Gulf Coastal Plain, Nebraska and Kansas. Kikoine (1948) reports it from the Campanian to the end of the Maestrichtian in the Pyrenees. This species is common in the cores from MP 27.

### GÜMBELINA PSEUDOTESSERA Cushman, 1938
Plate 30, fig. 14

*Gümbelina pseudotessera* CUSHMAN, 1938, Cushman Lab. Foram. Res. Contr., vol. 14, p. 14, pl. 2, figs. 19–21.

*Gümbelina pseudotessera* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 106, pl. 45, figs. 16–20.

This species is rare in the cores from MP 27. The geologic range of the species is from the Austin to upper Taylor in the Gulf Coast and adjacent areas.

### GÜMBELINA aff. G. MIDWAYENSIS Cushman, 1940
Plate 31, figs. 7, 8

*Gümbelina midwayensis* CUSHMAN, 1940, Cushman Lab. Foram. Res., Contr., vol. 16, p. 65, pl. 11, fig. 15.

This form occurs rarely in the indurated *Globigerina* ooze from Hess Guyot. It is similar to Cushman's Alabama species except in size. The average dimensions of ten specimens from the Hess Guyot fauna are: length 0.35 mm., width 0.20 mm., thickness 0.15 mm. These dimensions are about twice those of the Alabama species. Cushman noted the chambers of *G. midwayensis* as "slightly overlapping" whereas the overlapping on the MidPac specimens is marked. The writer considers the MidPac specimens to be either conspecific with *G. midwayensis* or very closely related.

### GÜMBELINA STRIATA (Ehrenberg), 1838
Plate 30, fig. 13

*Textilaria striata* EHRENBERG, 1838, K. preuss. Akad. Wiss. Berlin, Abh., p. 135, pl. 4, 1a, 2a, 3a.
*Gümbelina striata* EGGER, 1899, K. bayer Akad. Wiss. Math.-naturh., Abt. Abh., Kl. 2, vol. 21, p. 33, pl. 14, figs. 37–39.
*Gümbelina striata* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 104, pl. 45, figs. 4, 5.
*Gümbelina striata* BANDY, 1951, Jour. Paleontology, vol. 25, p. 510, pl. 75, figs. 8a–b, 9a–b.

This species is rare in the cores from MP 27, it is reported from the Austin to Navarro in the Gulf Coast and adjacent areas and from the Coniacian into the Maestrichtian of Europe.

### GÜMBELINA ULTIMATUMIDA
White, 1929
Plate 31, figs. 1–4

*Gümbelina ultimatumida* WHITE, 1929, Jour. Paleontology, vol. 3, p. 39, pl. 4, fig. 13.
*Gümbelina pupa* CUSHMAN (not Reuss), 1927, Jour. Paleontology, vol. 1, p. 157, pl. 27, figs. 6a–b.
*Gümbelina ultimatumida* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 107, pl. 46, figs. 6, 7.

This species is very common in the indurated *Globigerina* ooze from Hess Guyot (MP 33 C) and is rare in the cores at MP 27. It is common in the Velasco and Mendez shales of Mexico and has been reported from the Upper Cretaceous and lower Tertiary of Trinidad and from the Upper Cretaceous to Eocene of New Jersey.

### GÜMBELINA VENEZUELANA Nuttall, 1935

*Gümbelina venezuelana* NUTTALL, 1935, Jour. Paleontology, vol. 9, p. 126, pl. 15, figs. 2–4.

This species is abundant in the Eocene cores from Horizon Guyot.

### Genus PSEUDOTEXTULARIA Rzehak, 1886
### PSEUDOTEXTULARIA VARIANS
Rzehak, 1895
Plate 30, fig. 9

*Pseudotextularia varians* RZEHAK, 1895, K. k. Naturh. Hofmus. Annalen, vol. 10, p. 217, pl. 7, figs. 1–3.
*Pseudotextularia varians* Rzehak CUSHMAN, 1946 U. S. Geol. Survey Prof. Paper 206, p. 110, pl 47, fig. 4–9.

One specimen of this species was found in the mixed Upper Cretaceous to Recent fauna from MP 27-2.

### Genus VENTILABRELLA Cushman, 1928
### VENTILABRELLA AUSTINANA
Cushman, 1938
Plate 30, fig. 7

*Ventilabrella austinana* CUSHMAN, 1938, Cushman Lab. Foram. Res., Contr., vol. 14, p. 26, pl. 4, fig. 19.
*Ventilabrella austinana* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 111, pl. 47, fig. 16.

This species is rare in the cores at MP 27. The genus ranges from the Turonian to the end of the Maestrichtian and occurs in the sediments of the Gulf Coast and adjacent areas and in Europe.

### VENTILABRELLA CARSEYAE Plummer, 1931
Plate 30, fig. 8

*Ventilabrella carseyae* PLUMMER, 1931, Texas Univ. Bull. 3101, p. 178, pl. 9, figs. 7–9, 10.
*Ventilabrella carseyae* CUSHMAN, 1946, U. S. Geol. Surv. Prof. Paper 206, p. 112, pl. 48, figs. 1–5.

This species is rare in the cores at MP 27; it is abundant in the rocks of Navarro age in the Gulf Coast and adjacent areas.

The following benthonic species is reported at this time because of its wide occurrence in the Mid-Pacific faunas and to call attention to its importance as a world-wide index fossil.

### EPONIDES TRÜMPYI Nuttall, 1930
Plate 31, figs. 22, 23

*Eponides trümpyi* NUTTALL, 1930, Jour. Paleontology, vol. 4, p. 287, pl. 24, figs. 9, 13, 14.

This species occurs rarely in the indurated *Globigerina* ooze from Hess Guyot, in the cores from MP 27, and in the cores from Horizon Guyot. Glaessner reports this species from the Caucasus; it is common in the Gulf Coast and Caribbean area, and its occurrence in the Middle Pacific further establishes it as a world-wide index fossil. The geologic range is reported to be Paleocene, all of the Eocene, and questionably lower Oligocene.

### NONION MICRUS Cole, 1928
Plate 30, fig. 4

*Nonion micrus* COLE, 1928, Bull. Am. Paleon., vol. 14, no. 51, p. 22, pl. 5, fig. 12.

One specimen assigned to this species occurred in the Eocene fauna from Horizon Guyot. For remarks concerning this species and *Globigerinella pseudovoluta* Bandy see comments under the latter species.

### REFERENCES

BANDY, O. L., 1951, Upper Cretaceous Foraminifera from the Carlsbad area, San Diego Co., Calif.: Jour. Paleontology, vol. 25, p. 488–513.

BARKER, R. W., 1936, Micropaleontology in Mexico, with special reference to the Tampico Embayment: Bull. Am. Assoc. Pet. Geol., vol. 20, p. 433–456.

BERMUDEZ, P. J., 1950, Contribucion al estudio del Cenozoico Cubano: Mem. Soc. Cubana Hist. Nat., vol. 19, no. 3.

BOLLI, H., 1951, *Globotruncana* in Trinidad, B.W.I.: Jour. Paleontology, vol. 25, p. 187–200.

BRADY, H. B., 1884, Report on the Foraminifera dredged by HMS *Challenger* during the years 1873–1876: Report Voy. *Challenger*, Zool., vol. 9.

BRONNIMANN, P., 1950, The genus *Hantkenina* Cushman in Trinidad and Barbados, B.W.I.: Jour. Paleontology, vol. 24, p. 397–420.

CUSHMAN, J. A., 1910–1916, A monograph of the Foraminifera of the North Pacific Ocean: U. S. Nat. Mus. Bull. 71, Pts. 1–6.

——, 1921, Foraminifera of the Philippine and adjacent seas: Bull. U. S. Nat. Mus., vol. 4, 608 pp.

——, 1925, Foraminifera of the tropical Central Pacific: Bull., Bernice P. Bishop Mus., no. 27, p. 121–144.

——, 1927, Some characteristic Mexican fossil Foraminifera: Jour. Paleontology, vol. 1, p. 147–173.

——, 1938, Cretaceous species of *Gümbelina* and related genera: Contr. Cushman Lab. Foram. Res., vol. 14, pt. 1, p. 2–27.

——, 1946, Upper Cretaceous Foraminifera of the Gulf Coastal Region of the United States and adjacent areas: U. S. Geol. Surv. Prof. Paper 206.

——, 1948, Foraminifera, their classification and economic use: Harvard Univ. Press.

GLAESSNER, M. F., 1937, Plankton Foraminiferen aus der Kreide und dem Eozan und ihre stratigraphische Bedeutung: Studies Micropaleon., vol. 1, p. 27–52.

——, 1943, Problems of stratigraphic correlation in the Indo-Pacific Region: Roy. Soc. Victoria, vol. 55, pt. 1(NS), p. 41–80.

——, 1945, Principles of micropaleontology, London.

GRIMSDALE, T. F., 1947, Upper Cretaceous Foraminifera: A criticism: Jour. Paleontology, vol. 21, p. 586–587.

—— 1951, Correlation, age determination, and the Tertiary pelagic Foraminifera: Proc., Third World Petroleum Congress, Section I, Preprint 7.

HESS, H. H., 1946, Drowned ancient islands of the Pacific Basin: American Jour. Sci., vol. 244, p. 772–791.

KUENEN, P. H., 1950, Marine geology. John Wiley and Sons, Inc., New York.

——, 1951, Properties of turbidity currents of high density: Soc. Economic Paleontologists and Mineralogists, Sp. Publ. No. 2, p. 14–34.

——, and MIGLIORINI, C. I., 1950, Turbidity currents as a cause of graded bedding: Jour. Geology, vol. 58, p. 91–127.

LADD, H. S., and TRACEY, J. I., JR., 1949, The problem of coral reefs: Scientific Monthly, vol. 69, no. 5.

LEROY, L. W., 1948, The foraminifer *Orbulina universa* d'Orbigny, a suggested middle Tertiary time indicator: Jour. Paleontology, vol. 22, p. 500–508.

MENARD, H. W., and LUDWICK, J. C., 1951, Applications of hydraulics to the study of turbidity currents: Soc. Economic Paleontologists and Mineralogists, Spec. Publ. No. 2, p. 2–14.

MUIR, J. M., 1936, Geology of the Tampico Region, Mexico: Am. Assoc. Petrol. Geol., Tulsa.

MURRAY, J., and LEE, G. V., 1909, The depth and marine deposits of the Pacific: Mem. Mus. Comp. Zool., vol. 38, p. 1–169.

NAKKADY, S. E., 1950, A new foraminiferal fauna from the Esna shales and Upper Cretaceous chalk of Egypt: Jour. Paleontology, vol. 24, p. 675–692.

NATLAND, M. L., 1933, The temperature and depth-distribution of some Recent and fossil Foraminifera in the southern California region: Bull. Scripps Inst. Ocean., Tech. Series, vol. 3, p. 225–230.

NOTH, R., 1951, Tentative correlation of the Upper Cretaceous of Austria with that of the Gulf Coast and Mexico: The Micropaleontologist, vol. 5, no. 4, p. 35–38.

NUTTALL, W. L. F., 1930, Eocene Foraminifera from Mexico: Jour. Paleontology, vol. 4, p. 271–293.

PHLEGER, F. B., 1951, Displaced Foraminifera faunas: Soc. Economic Paleontologists and Mineralogists, Spec. Publ. No. 2, p. 66–76.

——, and PARKER, F. L., 1951, Ecology of Foraminifera, northeast Gulf of Mexico: Geol. Soc. America, Memoir No. 46.

REVELLE, R. R., 1944, Marine bottom samples collected in the Pacific Ocean by the *Carnegie* on its seventh cruise: Carnegie Inst. of Washington Publ. 556.

SALAS, G. D., 1949, Geology and development of Poza Rica oil field: Bull. Amer. Assoc. Petrol. Geol., vol. 33, p. 1385–1409.

SHEPARD, F, P., 1948, Submarine geology. Harper & Bros., New York.

STAINFORTH, R. M., 1948, Applied micropaleontology in coastal Ecuador: Jour. Paleontology, vol. 22, p. 113–151.

——, 1950, Is more concerted effort possible in establishing regional significance of planktonic

Foraminifera as indices of geologic age?: The Micropaleontologist, vol. 4, p. 18.

Thalmann, H. E., 1934, Die regional-stratigraphische Verbreitung der oberkretazischen Foraminiferan-Gattung *Globotruncana* Cushman 1927: Eclo. Geol. Helv, vol. 27, p. 413–428.

——, 1935, Age of the Velasco formation in eastern Mexico: Proc. Geol. Soc. Am. for 1934, June, 1935, p. 371.

——, 1942a, *Globotruncana* in the Franciscan limestone, Santa Clara Co., California: Bull. Geol. Soc. America, vol. 53, p. 1838.

——, 1942b, *Hantkenina* in the Eocene of East Borneo: Stanford Univ. Pub. Geol. Sci., vol. 3, p. 1–24.

——, 1942c, Foraminiferal genus *Hantkenina* and its subgenera: American Jour. Sci., vol. 240, p. 809–820.

White, M. P., 1928–29, Some index Foraminifera of the Tampico Embayment area of Mexico: Jour. Paleontology, vol. 2, p. 177–215; vol. 2, p. 280–317; vol. 3, p. 30–58.

## REFERENCES (IN ADDITION TO THOSE ABOVE) USED IN DETERMINING GEOLOGIC RANGES OF SPECIES

Applin, E. R., and Jordan, L., 1945, Diagnostic Foraminifera from subsurface in Florida: Jour. Paleontology, vol. 9, p. 129–148.

Bermudez, P. J., 1949, Tertiary smaller Foraminifera of the Dominican Republic: Cushman Lab. Foram. Res., Spec. Publ. No. 25.

Bronnimann, P., 1951, The genus *Orbulina* d'Orbigny in the Oligo-Miocene of Trinidad, B.W.I.: Contr. Cushman Found. Foram. Res., vol. 2, p. 132–138.

——, 1952, Globigerinidae from the Upper Cretaceous (Cenomanian-Maestrichtian) of Trinidad, B.W.I.: Bull. American Paleon., vol. 34, no. 140.

Brotzen, F., 1948, The Swedish Paleocene and its foraminiferal faunas: Sverig., geol. Undersokn., ser. C, no. 493, Arsbok 42, no. 2.

Cushman, J. H., and Renz, H. H., 1946, The foraminiferal fauna of the Lizard Springs formation of Trinidad, B.W.I.: Cushman Lab. Foram. Res., Spec. Publ. No. 18.

Galloway, J. J., and Heminway, C. E., 1941, The Tertiary Foraminifera of Porto Rico: N. Y. Acad. Sci., Sci. Survey of Porto Rico and the Virgin Is., vol. 3, pt. 4.

Jennings, P. H., 1936, A microfauna from the Monmouth and basal Rancocas group of New Jersey: Bull. American Paleon., vol. 33, no. 78.

Kikoine, J., 1948, Les Heterohelicidae du Cretace Superieur Pyreneen: Bull. Soc. Geol. France, ser. 5, vol. 18, p. 15–35.

Plummer, H. J., 1936, Foraminifera of the Midway formation in Texas: Univ. of Texas Bull. No. 2644.

Renz, H. H., 1948, Stratigraphy and fauna of the Agua Salada group, Venezuela: Geol. Soc. America, Mem. No. 32.

Schijfsma, F., 1946, The Foraminifera from the Hervian (Campanian) of southern Limburg: Meded. Geol. Sticht., ser. C, vol. 5, no. 7.

Wicher, C. H., 1949, On the age of the higher Upper Cretaceous of the Tampico Embayment area in Mexico: Bull. Mus. Hist. Nat., Pays Serbe, ser. A, livre 2, p. 49–105.

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# RAFTED PEBBLES FROM THE DEEP OCEAN OFF BAJA CALIFORNIA

BY

GEORGE A. SHUMWAY

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FIGS. 1–3, MARCH, 1953

# RAFTED PEBBLES FROM THE DEEP OCEAN OFF BAJA CALIFORNIA[1]

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## ABSTRACT

Fifty-three pebbles and small cobbles, and several pieces of asphalt, were dredged from the deep Pacific Ocean 60 nautical miles southwest of Cedros Island, Baja California, at a depth of about 2100 fathoms. Thirteen of the rocks are igneous, 12 are metamorphic, and 28 are sedimentary. More than half of the pieces are rounded or sub-rounded. Eighteen sedimentary pieces contain holes or portions of holes due to the activities of boring animals such as pholads. An analysis of the asphalt failed to indicate if it is of natural origin or a refined product.

The varied lithology, the rounding of a large number of pieces, and the pholad-type borings indicate that the rocks have been transported from a shallow-water environment to the deep sea. Several transporting mechanisms are discussed. Rafting of the rocks by floating kelp is the most likely means of transport.

## INTRODUCTION

The 53 pebbles and small cobbles and the pieces of asphalt described in this paper were accidentally dredged from the floor of the deep sea by a trawl designed to obtain biological specimens in the midwater regions. The Scripps Institution of Oceanography research vessel *Paolina T* made a biological cruise in the Pacific Ocean southwest of Cedros Island, Baja California (fig. 1), in November-December 1951. R. L. Wisner attempted to trawl in the deep water near the sea floor but the trawl dragged bottom at a depth between 2000 and 2200 fathoms. Red clay was found in the trawl when it was brought back to the deck. Within the clay Wisner discovered the pieces of rock, the asphalt, and a few manganese dioxide nodules. He turned over the material to F. P. Shepard and R. S. Dietz, who gave it to the writer to investigate.

The material obtained with the trawl is an unusual deep sea bottom sample. The varied lithology of the pieces of rock, the rounding, and the pholad-type holes are indicative of a shallow water marine environment. Consideration of possible mechanisms which might have carried the pebbles and small cobbles to the deep water leads to the conclusion that kelp rafting is the most likely process. Kelp rafting has usually been considered a somewhat "academic" sedimentary process, but this material from the deep sea indicates that the process may be one of significance.

### *Location*

The trawling was done on the gently elevated sea floor on the southwest side of Cedros Deep, between Lat. 27° 11.4′ N, Long. 116° 30.6′ W and Lat. 27° 31.7′ N, Long. 115° 54.9′ W (fig. 1). The continental slope southwest of Cedros Island is steep, with a dip of 10 degrees between the 200 and 2400 fathom contours. On the seaward side of the trough the sea floor rises gently, and it is in this area that the trawl dragged bottom, at a depth between 2000 and 2200 fathoms.

### *Possible Number of Rocks Per Unit Area on Sea Floor*

The Isaacs-Kidd midwater trawl which obtained the sea floor sample is designed to obtain biological specimens in the midwater regions and is not intended for

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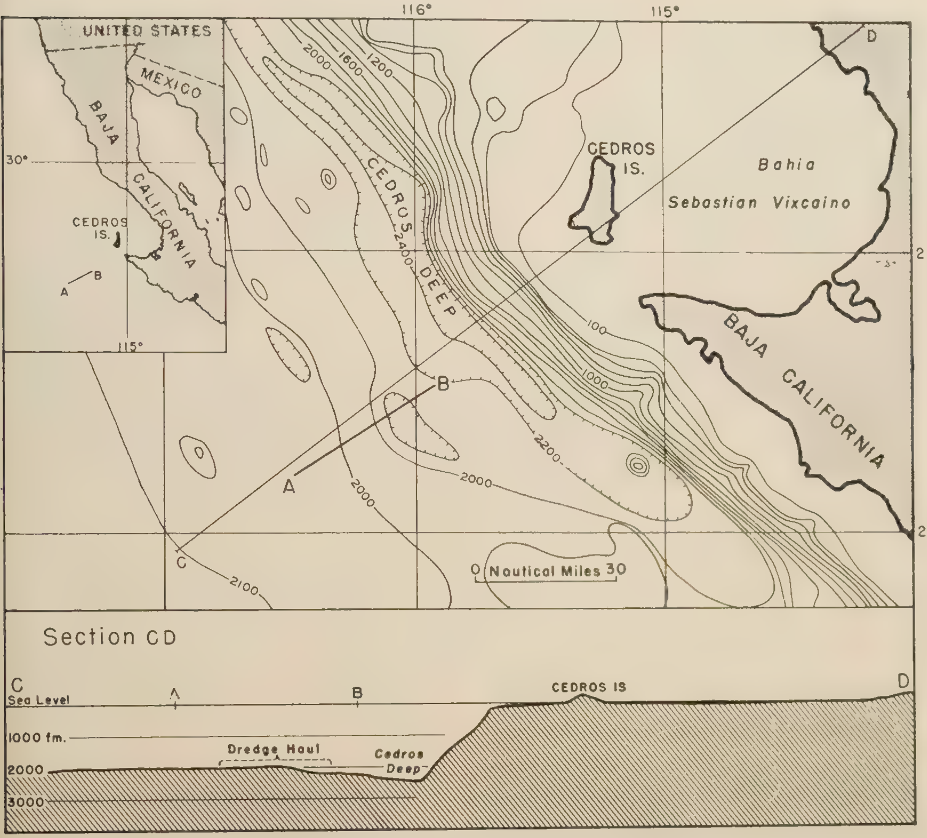
[1] Navy Electronics Laboratory Professional Contribution no. 4. Contribution from the Scripps Institution of Oceanography, New Series No. 616.


116°
115°
UNITED STATES
MEXICO
BAJA
CALIFORNIA
30°
CEDROS IS.
B
A
115°
2000
1600
1200
CEDROS
2400
DEEP
CEDROS IS.
Bahia
Sebastian Vixcaino
28°
100
1000
B
2200
2000
A
2000
27°
C
2100
0 Nautical Miles 30
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BAJA CALIFORNIA
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C
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CEDROS IS
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Dredge Haul
Cedros Deep
2000
3000

FIG. 1.—Location of trawling off Baja California where rocks and asphalt were obtained. Line AB represents distance covered by ship while trawl was in water. Section CD locates probable limits for the dredging.

use as a bottom dredge. It consists of a large tapering net with a rectangular opening 10 feet wide on the bottom edge. If it is assumed that the trawl effectively sieved a 10-foot swath of sediment for the entire distance it was towed at maximum depth, a calculation of the minimum number of rocks per unit area of the sea floor in the area dredged can be made. This assumption is thought to be unrealistic because it is likely that the trawl bounced and skipped along the bottom, probably only touching more elevated portions of the sea floor, digging into the sediment irregularly and sieving to some extent as it did so. Nevertheless, a calculation based on the maximum possible area dredged will give a minimum limit to the number of rocks per unit area, if the rocks are randomly distributed.

The ship moved approximately 37 nautical miles while the trawl was in the water (fig. 1), but a maximum of 3000 fathoms of cable was out for only about 15 nautical miles. Multiplying 15 nautical miles by the 10-foot width of the trawl gives an area of 0.033 square miles or 0.086 square km. Since 53 pieces of rock were obtained, the minimum density is 1600 rocks per square mile or 616 per square km. The actual density is thought to be much higher because it is very unlikely that the trawl sieved a

10-foot swath for 15 nautical miles of the sea floor.

### ACKNOWLEDGMENTS

R. L. Wisner recognized the unusual nature of the pebbles he accidently obtained from the sea floor and his preservation of the material for study by marine geologists is appreciated. Rollin Eckis, Clifton W. Johnson and C. T. Brown of the Richfield Oil Corporation made possible the analysis of the asphalt and their help and interest are acknowledged. William R. Riedel kindly identified radiolaria from a limestone pebble. Garret L. Prible aided in drafting.

Francis P. Shepard and M. N. Bramlette have critically read the manuscript. Robert S. Dietz and Henry W. Menard discussed the subject matter with the author, suggested changes in the manuscript, and read the final manuscript.

### DESCRIPTION OF SEDIMENT FROM THE TRAWL

#### *General Statement*

Figure 2 is a photograph of all of the coarse material brought up by the trawl. The pebbles and small cobbles consist of an assortment of igneous, metamorphic, and sedimentary rocks. Pieces of a brittle asphalt and a few manganese dioxide nodules were obtained in addition to the rocks. The rounded pebbles can be noted in figure 2 and the pholad-type holes in figures 2 and 3. Thin sections of the igneous and metamorphic rocks have been examined, and an analysis of the asphalt has been made.

The three most significant features of the group of rocks are the varied lithology, the rounding of a number of pieces, and the animal borings. Each of these features is suggestive of the shallow-water environment near the coast, where rocks from various formations along the coast are mixed together and abraded.

#### *Rock Types*

Of the fifty-three pebbles and small cobbles, 13 are igneous, 12 are metamorphic, and 28 are sedimentary. The igneous pieces include diorites, tonalites, and rhyolites, but basalt is not present.

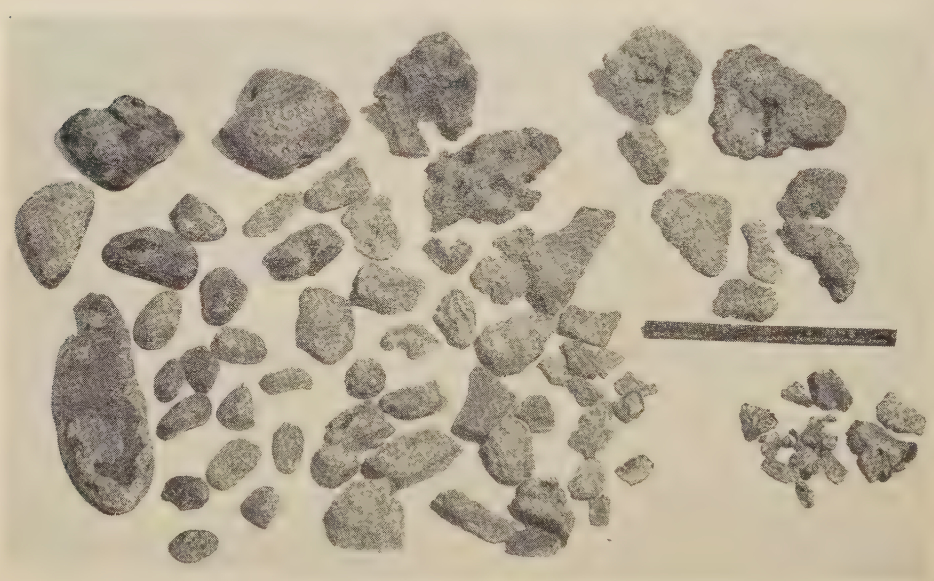

FIG. 2.—Pebbles, asphalt and manganese dioxide nodules from the deep ocean off Baja California. Igneous, metamorphic and sedimentary rocks are present. Note pholad-type borings in some pebbles. At lower right, below scale, are pieces of asphalt.

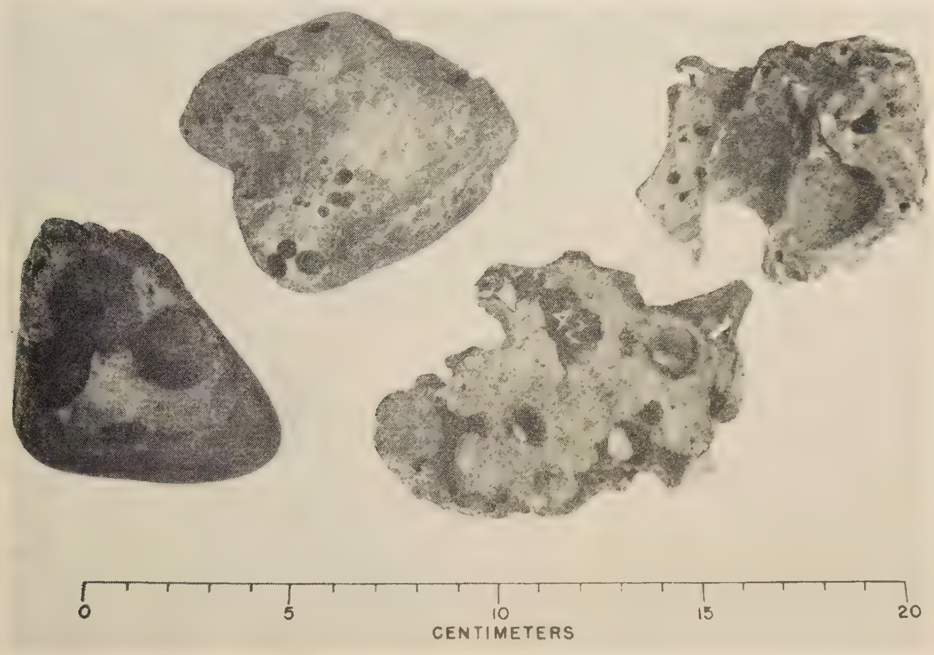

FIG. 3.—Sedimentary rocks with pholad-type borings. Note that one piece has been bored after being rounded.

Volcanoes of the Pacific petrographic province produce olivine basalt and petrographically related rocks; hence the absence of such rocks suggests a continental origin for the dredged-up rocks. Metamorphic pieces include a hornblende gneiss, quartzites, graywackes, and a silicified black shale. Sandstone and siltstone dominate in the sedimentary suite. Two pieces of tuff and one limestone piece are also present. William R. Riedel examined the calcareous rock and found that it contained Miocene radiolaria.

Table 1 lists the igneous and metamorphic rocks and gives an indication of the roundness of each fragment as a number based on visual comparison of the pieces with a chart devised by Krumbein (1941). Table 2 lists the sedimentary pieces with regard to rock classification and any important features which they may have, such as animal borings.

### *Animal Borings*

At least eighteen of the pebbles and small cobbles contain holes or portions of holes which have resulted from the activities of marine boring animals. Many of the holes closely resemble the type produced by the pholads—a circular cavity which increases in diameter with depth. The holes can be seen in a number of pebbles illustrated in figure 2. Figure 3 shows more closely the extent of borings in four of the larger pieces. Some of the rocks containing holes have been rounded prior to the development of the holes. No calcareous shells or hole linings were found in any of the cavities. Pholads and other boring animals usually choose shales, siltstones and sandstones in which to make their burrows, in preference to igneous and metamorphic rocks which are harder. All of the eighteen pieces which contain holes are relatively soft sedimentary rocks.

TABLE 1.—*Igneous and metamorphic rocks*

| Igneous rocks | Roundness |
|---|---|
| Diorite | .8 |
| Diorite | .7 |
| Diorite | .4 |
| Diorite | .2 |
| Diorite porphyry | .4 |
| Tonalite | .7 |
| Tonalite | .5 |
| Tonalite | .1 |
| Syenite porphyry | .8 |
| Calci-alkalic granite | .2 |
| Rhyolite | .8 |
| Rhyolite | .7 |
| Rhyolite | .2 |
| Metamorphic rocks | |
| Hornblende gneiss | .3 |
| Arkosic quartzite | .4 |
| Quartzite | .5 |
| Greywacke | .4 |
| Greywacke | |
| Greywacke | |
| Greywacke | |
| Silicified black shale | .5 |
| Quartz, unidentified rock | .6 |
| Unidentified | .2 |
| Unidentified | .2 |
| Unidentified | .1 |

Pholads are known to inhabit rocks in the lower intertidal zone and are abundant on the sea floor of the adjacent inner neritic zone. They are considered characteristic of shallow waters, although even generalized depth limits are not well known. Pholads are abundant in the rocky sides of Scripps Submarine Canyon off La Jolla, California to depths of 140 feet according to the writer's underwater observations. The rocky sea floor where kelp plants attach themselves contains a large population of pholads. *Pholadidea penita* has been dredged from a depth of 50 fathoms in San Francisco Bay (Hill and Kofoid, 1927).

Hanna (1952) discusses borings in rocks dredged from the continental slope off San Francisco, California. He found pholad-type borings in rocks from as deep as 600 fathoms but neither the animals nor remains of their shells were present. He considers pholads to be shallow water animals and, for lack of another explanation, attributes the deep occurrences of bored rocks to subsidence. On Station 51, at a depth between 180 and 80 fathoms, Hanna dredged up sandstone with numerous cavities containing the "nestling" mollusk, *Saxicava.*

The presence of animal borings, many which are the pholad type, in eighteen of the rocks brought up by the trawl, is a good indication that these rocks were transported from the near-shore marine environment to the deep water where they were found.

TABLE 2.—*Sedimentary rocks*

| |
|---|
| Sandstone, grains up to 0.5 mm. dia., arkosic |
| Sandstone, grains up to 0.5 mm. dia., arkosic |
| Sandstone, graded bedding medium fine grains to silt |
| Sandstone, fine grained, arkosic |
| Sandstone, fine grained |
| Sandstone, fine grained, arkosic, many animal borings |
| Sandstone, fine grained, animal borings, impregnated with $MnO_2$ |
| Sandstone, fine grained, micaceous, animal borings |
| Sandstone, fine grained, animal borings, $MnO_2$ coating 2–3 mm. |
| Sandstone, fine grained, animal borings, $MnO_2$ coating 2–3 mm. |
| Sandstone, fine grained, dark minerals, $MnO_2$ coating 2–4 mm. |
| Sandstone, very fine grained, micaceous, animal borings |
| Siltstone, biotite present, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, biotite present, animal borings |
| Siltstone, specimen rounded, many animal borings |
| Siltstone, specimen rounded, large animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, animal borings |
| Siltstone, micaceous, animal borings, $MnO_2$ coating 2–3 mm. |
| Siltstone, biotite present |
| Siltstone, $MnO_2$ coating 3–5 mm. |
| Limestone, contains Miocene radiolaria |
| Tuff, fine particle, size, animal borings |
| Tuff, very fine particle size |
| Manganese dioxide nodule without rock nucleus |
| Manganese dioxide nodule without rock nucleus |
| Manganese dioxide nodule without rock nucleus |

### *Manganese Dioxide Coatings*

All of the rocks brought up in the trawl were coated with manganese dioxide. The coating was only a fraction of a millimeter thick on the rounded pieces of igneous and metamorphic rock, but was 1 to 5 mm thick on some angular pieces of siltstone and sandstone. A few pieces of sandstone, when broken open, revealed spots of manganese dioxide throughout the rock. The oxide appeared to be growing within the porous material. Three manganese dioxide nodules were included in the trawl which did not contain visible rock fragments for nuclei.

### *Red Clay and Its Contents*

Red clay is the usual sediment in the area dredged, judging from the greater part of the sediment brought up in the trawl. This agrees with Revelle's map (1944) of bottom sediments of the Pacific Ocean. A small amount of detrital material and an appreciable amount of organic remains were present in the sample examined. The organic remains include worm tubes, diatoms, radiolaria, fragments of fish teeth, tiny pelecypod shells, pelagic and benthonic Foraminifera tests, bone fragments, and echinoid plates. The detrital material consisted of a very few mineral and rock grains.

### *Foraminifera*

The Foraminifera within the red clay were examined with the idea that a displaced benthonic fauna might be found. The presence of a displaced, relatively shallow-water, fauna would suggest that sediment had been carried down the continental slope, across the bottom of the Cedros Deep trough, and up the gentle rise on the seaward side of the trough by a turbidity current or mass movement of sediment. Typical and indicative shallow-water species were not found among the benthonic fauna and therefore the fauna appears to be indigenous.

### *Asphalt*

Pieces of brittle asphalt (fig. 2) were included in the trawled material. Rollin Eckis of the Richfield Oil Corporation had some of the the asphalt analyzed in Richfield's Watson Laboratory to determine if possible whether it was a natural asphalt or a refined petroleum product. C. T. Brown of Watson Laboratory reported the following data: Acid No. 5.7; Saponification No. 8.7; Sulfur 7.24%. An acid number less than one suggests a refined product and 2–15 a natural product but saponification numbers less than 15 suggest refined products. Thus the two points are contradictory. The brittle asphalt gave a clean, bright surface when broken and Brown felt that an underwater seepage of asphalt would be spongy and porous. His guess is that the asphalt probably did not occur naturally at the site where it was found.

Small quantities of a soft, black, tarry bituminous substance are frequently found in the sediments of California's continental borderland basins. Emery and Rittenberg (1952) discuss this material, which they noted in 85 out of 280 bottom samples they examined. They describe it as separate grains 0.2 to 2 mm in diameter or as a cement for detrital grains and Foraminifera tests. They found that its distribution showed no relation to depth of water or to kind of enclosing sediment (however, their studies were only of basin sediments, which usually occur at less than 1000 fathoms), and only a slight relation to oil producing areas on land. Some of the bituminous matter came from deep in cores, so the influence of men and ships can be discounted. It is known that early Indians of California made use of bitumen they collected along beaches for such purposes as lining bowls.

Perhaps the brittle asphalt dredged from the deep sea is in some way related in origin to the type of bituminous matter found in the basin sediments off southern California.

## MODE OF TRANSPORTATION

### *General Statement*

The nature of the pebbles indicates

that they probably were transported from a shallow water environment to the floor of the deep sea. The greater part of the sediment brought up by the trawl is red clay, containing a small amount of organic matter and a few detrital grains; this is the typical sediment for the area. The pebbles and small cobbles have resulted from a rather unusual sedimentary process which is independent of the processes which deposited the fine sediment in the area.

Agassiz (1902, p. 72) was puzzled by pebbles dredged up by the *Albatross* on its 1899–1900 cruise at a location approximately 570 nautical miles west of the position for the rocks described in this paper. Red clay, manganese dioxide nodules, flat slabs of palagonite tuff and some pebbles thinly coated with manganese dioxide were obtained from a depth of 2368 fathoms. The pebbles consisted of a portion of a rounded pebble of hornblende andesite, fragments of a well rounded pebble of black chert traversed by minute quartz veins, a subangular fragment of pale-green serpentine, and an angular fragment of fine-grained sandstone. The similarity between these pebbles and the ones described in this paper is close with regard to lithologic types represented and external form. No mention of animal borings is made by Agassiz. The two occurrences may or may not be due to a common sedimentary process.

### *Possible Methods of Emplacement of the Pebbles*

*Turbidity current or mass movement transport.*—Turbidity currents and mass movements under favorable conditions are believed to be capable of transporting sand and perhaps coarser materials down the continental slopes and out onto the deep sea floor. The continental slope is steep off Cedros Island, with a 10 degree dip, and should be capable of furthering the progress of any such processes which might originate on the slope. However, the location of the pebbles southwest of Cedros Deep, 300 to 400 fathoms above the lowest part of the trough, presents an obstacle to the mechanism. It might be considered that the pebbles were transported before the trough developed, but if this had happened they probably would be too deeply buried in sediment to be obtained with a dredge.

The large size of the pebbles relative to the fine sand that is usually carried out onto the deep sea floor and ascribed to turbidity currents is considerable, and would indicate a very capable transporting mechanism. If the pebbles had been transported by turbidity current action it would seem that smaller pebbles, coarse, medium, and fine sand and shallow water benthonic Foraminifera would have been deposited along with the coarse material. With the exception of a few coarse rock grains these finer fractions are not present and a displaced benthonic Foraminifera fauna is not evident. Thus, turbidity currents and mass movements are an unlikely cause for the rocks being in the deep sea.

*Subsidence of submarine bank.*—Tertiary and Quaternary movements of land off southern California have been of such significant magnitudes that the possibility of the subsidence of a submarine bank might be considered responsible for the pebbles. The continental borderland off southern California is considered to have broken up and subsided in the Miocene (Emery and Shepard, 1945) but the present submerged continental area is generally at less than 1000 fathoms and is elevated by about 1000 fathoms from the true deep sea floor. It is considered unlikely that a continental area off Baja California has sunk away to become a part of the deep sea floor, but if such an event has happened it might explain the presence of the pebbles.

Two banks, Fortymile Bank and Thirtymile Bank, lie off San Diego at distances implied by their names. The summits of these banks lie at 43 and 130 fathoms respectively. At a depth of 210 fathoms on Fortymile Bank rounded cobbles and a piece of rock containing pholad-type holes have been dredged.

The rounding and pholad-type holes are apparently not due to processes acting at the present time and may have resulted from sinking of the bank or from a lowered sea level during the Pleistocene. If such banks were to be submerged to 2100 fathoms and remain free of excessive sediment, then a dredge haul made near the summit of one might obtain an assemblage of fragments similar to those here described.

Two considerations tend to discredit the subsidence argument. A subsidence of land of the order of 2000 fathoms, to become a part of the deep sea floor, is inconsistent with the theory of permanency of the ocean basins. The second consideration is that no phosphorite was found among the group of rocks, yet this authigenic mineral is commonly present on topographic highs in the continental borderland region. If a submarine bank in the continental borderland region had become deeply submerged it probably would contain pieces of phosphorite together with abraded rock fragments, and a sample of more than 50 pieces should include some phosphorite.

*Ice rafting.*—Rafting of glacially rounded rock fragments by icebergs has left pebbles, cobbles and boulders widely disseminated on a portion of the floor of the North Pacific Ocean. According to Menard (personal communication), any dredge haul taken in the Gulf of Alaska almost invariably brings up ice-rafted material except in near-shore areas where deposition of terrigenous materials has been rapid enough to bury the Pleistocene sediments. The southern limit of glacial-marine sediments is approximately 48 degrees north latitude (Menard, in press) but a few icebergs probably were carried farther south by the ocean currents which transport water southward off the western coast of North America. If the pebbles from near Cedros Deep or from the *Albatross* sample are of ice-rafted origin then they represent the most southernly occurrence of glacial-marine sediment yet reported in the North Pacific Ocean.

Agassiz (1902, p. 72) considers that the fragments he described from the deep sea west of Baja California have all the characteristics of glacial-worn pebbles, and gives the following discussion concerning their origin in the deep sea:

> "As the shark's teeth and cetacean bones found in the red clay seem to indicate that since the Tertiary times there have been very insignificant deposits at great distances from the continental areas, similarly we may be tempted to assume that these pebbles, which could not have been transported to their present locality by any agency of the present epoch, were carired to it during the glacial epoch, the thin coating of manganese dioxide indicating how small have been the bottom deposits since the glacial period."

The assumption of glacial origin for these pebbles is not unreasonable. The point concerning the thin coating of manganese dioxide as an indication of the small rate of accretion of the material since the glacial period is not necessarily valid, however. On Gilbert Seamount in the Gulf of Alaska, Menard (personal communication) found ice-rafted pebbles which had only a thin wash of manganese dioxide in more than 99 per cent of the cases, yet ice-rafted pebbles were also found several inches deep in pieces of manganese dioxide crust.

The presence of pholad-type holes in 18 out of the 53 pebbles from the sea floor off Cedros Island is notable because these features have not been found in any of a large number of ice-rafted pebbles, cobbles, and boulders from the Gulf of Alaska, according to Menard (personal communication). It would seem that the presence of a high percentage of pholad-type holes implies a non-ice-rafted origin for the pebbles described in this paper and the great distance from the Gulf of Alaska helps strengthen the argument.

*Kelp rafting.*—The ability of floating kelp to transport pebbles and small cobbles has been discussed by Emery and Tschudy (1941). Kelp is a form of marine algae which attaches itself to the sea floor in waters from about 20 to 90 feet in depth by means of root-like holdfast structures. The plant extends upward to the surface where its photosynthetic tissue can function best. The plants grow to a size of a hundred or more feet in length, and *Macrocystis*, the largest of the marine algae, commonly is 200 feet long and occasionally longer. In a number of species, gas filled floats keep the long blade of the plant near the surface. The float cavity of *Pelagophycus*, a species common off southern and Baja California, is reported by these authors to be as large as 120 cubic inches. The buoyancy of entire plants is considerable. Kelp grows almost exclusively on rocky bottoms because of the necessity of a good anchorage to prevent being carried away by currents. It often grows in extensive beds at depth between 30 and 90 feet, and the sea floor below these kelp beds usually consists of bedrock and loose boulders, cobbles and pebbles. Pholads and other boring animals are extremely abundant in these rocky areas, according to the author's observations while diving with the aid of an Aqua-lung.

Kelp plants are often torn loose from the bottom and washed ashore during storms. Pebbles are commonly found attached to the holdfasts. Emery and Tschudy estimated that more than 100 pebbles with holdfasts attaches were washed ashore at La Jolla after one day of large waves in 1940. In one of their illustrations these authors show photographs of some of the pebbles with holdfasts attached. The pebbles are both angular and rounded, and one piece contains worm and pholad borings.

Kelp beds are present along the Pacific coast from Alaska to south of Mexico. The circulation of surface water off Baja California provides the needed mechanism to carry the floating kelp out to sea. Throughout a good part of the year the currents move the surface waters southward along the coast of Baja California and at times turn seaward in the vicinity of Cedros Island.

Pholads are also found from Alaska to Central America and even farther south. According to Ricketts and Calvin (1939, p. 105–106), *Pholadidea ovoidea* is found from the Bering Sea to the Gulf of California, *P. penita* from Alaska to Ecuador, and *Saxicava pholadis* from the Arctic to Panama. The widespread occurrence of pholads and kelp in the same environment suggests that kelp-rafted rocks should contain a significant proportion of pieces with borings in them.

Kelp is frequently found floating far from land. A considerable amount of kelp was noted at sea off Baja California in August 1952 by the author while participating in Expedition Shellback of the Scripps Institution of Oceanography. A mat of kelp about 15 by 15 feet in size was sighted 34 nautical miles from land (Lat. 24° 30′N, Long. 112° 50′W) off Cape San Lazaro. Isolated pieces were sighted occasionally as the ship moved from this position up to Cedros Island. About 55 nautical miles north of Cedros Island and 21.5 nautical miles from land numerous pieces of kelp were sighted from the ship. A quantitative estimate of the number of pieces per unit area was made by counting pieces apparently greater than three feet long which passed within about 150 feet of the ship during a 15 minute period as the ship moved along at 11.5 knots. Fifty-one pieces were counted, implying 240 pieces per square nautical mile over the distance covered.

Emery and Tschudy (1941) mention kelp being seen 250 miles from land off southern California. In 1951 during the joint Scripps Institution of Oceanography-U. S. Navy Electronics Laboratory expedition, Northern Holiday, numerous pieces of kelp were sighted at distances as great as 300 miles from land. A number of pieces were picked up and one of them had a rock attached measuring 8 by 5 by 4 cm. All of the pebbles described in this paper are of a size that floating kelp could easily transport. Boulders and large cobbles are easily rafted by ice but there is a limit to the buoyancy of kelp plants. The absence of boulders and large cobbles in the sample favors kelp rafting. It is therefore reasonable that the pebbles described in this paper were transported by floating kelp, and of all the arguments considered, kelp rafting has the most points in its favor. The pebbles described by Agassiz (1909) may also be due to kelp rafting, but they were found about 600 nautical miles from land rather than 60 nautical miles.

## REFERENCES

Agassiz, A. (1902) Preliminary report and list of stations: Harvard Coll. Mus. Comp. Zoology, Mem., vol. 26, no. 1, 144 pp.

Emery, K. O., and Rittenberg, S. C. (1952) Early diagenesis of California basin sediments in relation to origin of oil: Am. Assoc. Petroleum Geologists Bull., vol. 33, no. 5, pp. 735–806.

Emery, K. O., and Shepard, F. P. (1945) Lithology of the sea floor off southern California: Geol. Soc. America Bull., vol. 56, pp. 431–478.

Emery, K. O., and Tschudy, R. H. (1941) Transportation of rock by kelp: Geol. Soc. America Bull., vol. 52, pp. 855–862.

Hanna, G D. (1952) Geology of the continental slope off central California: Proc. California Acad. Sci., 4th ser., vol. 27, no. 9, pp. 325–358.

Hill, C. L., and Kofoid, C. A. (1927) Marine borers on the Pacific coast, final part: San Francisco Bay Marine Piling Committee, 357 pp.

Krumbein, W. C. (1941) Measurement and geological significance of shape and roundness of sedimentary particles: Jour. Sedimentary Petrology, vol. 11, pp. 64–72.

Revelle, R. R. (1944) Marine bottom samples collected in the Pacific Ocean by the *Carnegie* on its seventh cruise: Carnegie Inst. Washington, Pub. 556, Washington, D. C., pp. 1–180.

Ricketts, E. F., and Calvin, J. (1939) Between Pacific Tides, Stanford Univ. Press, Stanford, Calif., 365 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 23, NO. 1, PP. 13–17
FIG. 1, MARCH, 1953

# EVIDENCE OF BIOCHEMICAL HEATING IN LAKE MEAD MUD[1]

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## ABSTRACT

Soft sedimentary material is rapidly accumulating on the bottom of Lake Mead in back of Hoover Dam across the Colorado River. The temperature of this sediment increases sharply with depth in the topmost layers, below which lower temperatures have been recorded with a special penetrating bathythermograph.

Bacterial thermogenesis appears to be responsible, at least in part, for the higher temperatures found in the sediment. Millions of living bacteria per gram were found in Lake Mead mud, the largest populations occurring in the topmost layers where the thermocline is steepest. Assuming that the bacteria generate heat at an average rate of $30 \times 10^{-12}$ calories per cell per hour, ten million might generate 2.6 calories in a gram of mud in a year.

Increases of a degree or more in temperature were noted in Lake Mead mud samples incubated for 20 days in thermos bottles, but little or no change occurred in similar mud that had been sterilized by autoclaving.

Oxygen and utilizable organic content affect the biochemical heating of mud.

## INTRODUCTION

Lake Mead, formed by Hoover Dam across the Colorado River on the Arizona-Nevada border, is rapidly filling with sediment (Gould, 1951). Bathythermograph tracings have revealed anomalous temperature gradients in the sediment. At the bottom of the lake where the bathythermograph entered the mud, there appeared to be a sharp temperature increase, which at certain stations was as much as 9°F. within the first five feet of penetration (Anderson and Pritchard, 1951).

Figure 1 shows a temperature-depth tracing made mid-channel a short distance upstream from Hoover Dam on 22 December 1948. During the descent of the bathythermograph, especially designed to penetrate the soft mud to a depth of nearly 100 feet, it registered temperatures increasing from 52.6°F. at the water surface to 53.8°F. at the mud-water interface. As the instrument entered the mud the temperature increased sharply within the topmost few feet. After reaching a maximum of 58.8°F. at a mud depth of about 30 feet, the temperature decreased with further penetration. The record made during the return of the instrument to the surface is probably in-

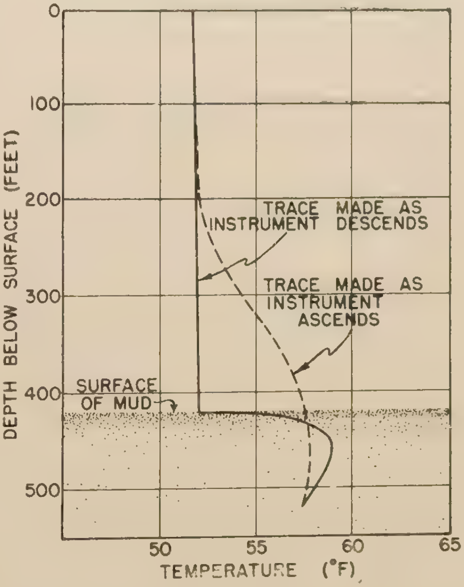

FIG. 1.—Bathythermograph tracings indicating heating in topmost few feet of Lake Mead mud.

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fluenced by the insulating effect of mud clinging to the thermal element; hence, it does not coincide with the descending record.

Neither heat conduction from the earth nor radioactivity seems to account for the sharp temperature increase near the mud surface. Therefore some consideration has been given to the possibility that heat generated by biochemical reactions catalyzed by bacteria in the mud may be partly responsible. Biochemical heating commonly occurs in compost piles, manure heaps, fermenting silage, and incompletely dried hay or grain (Miehe, 1911; James *et al.*, 1928; Gilman and Barron, 1930; Wedberg and Rettger, 1941). Many creatures in nature take advantage of heat generated by bacteria in decomposing materials to give increased temperatures favorable for the incubation of their eggs or offspring.

### BACTERIAL POPULATION OF MUD

Samples were collected mid-channel from fifty to a hundred yards upstream from Hoover Dam by means of a modified Ekman sampler. The apparatus consisted essentially of a plastic cylinder 30 inches long and two inches in diameter rigged to penetrate the mud in a vertical position with both ends open. It was lowered from a boat equipped with a cable and winch. When the desired depth was reached, a heavy messenger sent down the cable activated a mechanism that simultaneously closed both ends of the plastic cylinder with rubber stoppers. Water as well as semi-fluid mud samples were collected with this apparatus.

Within an hour after their collection, several samples serially diluted with sterile water were introduced into nutrient media in a field laboratory at Boulder City. It was necessary to complete the bacteriological analysis of the samples at La Jolla a day or two after their collection. In order to minimize changes in the microflora that may occur in such samples during storage (ZoBell, 1946) they were held at about 40°F. The inoculated media were incubated at 82°F. for 20 days, after which they were examined for evidence of bacterial growth or physiological activities of various kinds in selective media.

The abundance of bacteria was estimated by the extinction dilution method, a procedure in which 1.0 gram of inocula, or dilutions thereof by powers of ten, were introduced into appropriate nutrient media. The reciprocal of the log of the lowest dilution that showed signs of bacterial activity was assumed to represent the most probable number of active organisms. For example, when bacterial growth occurred in duplicate tubes of nutrient medium inoculated with 1.0, $10^{-1}$, $10^{-2}$, or $10^{-3}$ grams of a given sample but no growth in similar medium inoculated with $10^{-4}$ grams of the same sample, it was assumed that the sample contained a

TABLE 1.—*Bacterial growth, indicated by plus sign (+), or lack of growth (−), in nutrient medium inoculated in duplicate (a and b) with diminishing amounts of water or mud from different depths below the mud-water interface at the bottom of Lake Mead*

| Amount of inocula | Water sample from surface | | Mud from 0.3 feet | | Mud from 46 feet | | Mud from 99 feet | |
|---|---|---|---|---|---|---|---|---|
| grams | a | b | a | b | a | b | a | b |
| 1.0 | + | + | + | + | + | + | + | + |
| $10^{-1}$ | + | + | + | + | + | + | + | + |
| $10^{-2}$ | + | + | + | + | + | + | + | + |
| $10^{-3}$ | + | + | + | + | + | + | + | + |
| $10^{-4}$ | − | − | + | + | + | + | + | + |
| $10^{-5}$ | − | − | + | + | + | + | + | + |
| $10^{-6}$ | − | − | + | + | + | + | + | + |
| $10^{-7}$ | − | − | + | + | − | − | − | − |
| $10^{-3}$ | − | − | − | − | − | − | − | − |

TABLE 2.—*Minimum numbers of various physiological types of bacteria per gram of Lake Mead mud as indicated by extinction dilution method with differential nutrient media*

| Physiological type of bacteria | Mud from 0.3 feet | Mud from 46 feet | Mud from 99 feet |
|---|---|---|---|
| Multiply in peptone medium | $10^7$ | $10^6$ | $10^6$ |
| Liquefy gelatin | $10^6$ | $10^5$ | $10^5$ |
| Hydrolyze starch | $10^3$ | $10^3$ | $10^3$ |
| Decompose cellulose | $10^2$ | $10^2$ | $10^3$ |
| Reduce nitrate to nitrite | $10^6$ | $10^5$ | $10^4$ |
| Reduce sulfate to sulfide | $10^3$ | $10^2$ | $10^4$ |
| Oxidize $H_2$ | $10^3$ | $10^2$ | $10^4$ |
| Ferment glucose | $10^7$ | $10^5$ | $10^5$ |

minimum of $10^3$ or 1000 bacteria per gram that grew in this particular medium. Similarly, as summarized in table 1, growth in the $10^{-6}$ or $10^{-7}$ dilutions of mud showed that these samples contained a minimum of $10^6$ or $10^7$ viable bacteria per gram respectively. That such estimates are minimal is stressed, because it is unlikely that any one medium could provide for the growth of all bacteria that might be present.

Not only were large bacterial populations found at all levels in the lake mud but also detected were physiological types that could attack several different kinds of organic and inorganic substances (table 2). Aerobic bacteria predominated in the topmost layers of mud where free oxygen and food were most plentiful. Most of the aerobes detected in deeper strata proved to be facultative forms whose activity must have been anaerobic *in situ*. From cumulative results, including direct microscopic counts that are generally from ten to a hundred times higher than cultural counts, it is estimated that the topmost layer of Lake Mead mud contained bacterial populations of the order of $10^7$ to $10^8$ cells per gram.

Based on the assumption that physiologically active aerobic bacteria, of the types commonly occurring in lakes, generate heat at an average rate of $30 \times 10^{-12}$ calories per cell per hour, $10^7$ bacteria in a gram of mud might generate heat at a rate of $30 \times 10^{-5}$ calories per hour. Multiplying this value by 8760, the number of hours in a year, gives 2.6 calories per year as the amount of heat generated by $10^7$ bacteria in a gram of mud. At this rate a bacterial population of $10^8$ bacteria would generate 26 calories per gram of mud per year. Although these values may be only probable orders of magnitude owing to many variable and some unknown factors that affect heat generation by bacteria, the calculations indicate that, in a well insulated system such as mud, bacteria could account for the rise in temperature recorded by the bathythermograph in the topmost few feet of mud (fig. 1).

The value $30 \times 10^{-12}$ calories of heat generated per bacterial cell per hour is believed to be conservative. It is derived from the data of ZoBell (1940a, b) on the rate at which organic substances occurring naturally in lake and sea water are oxidized by bacteria, the average rate being $20 \times 10^{-12}$ mgm per cell per hour at 78°F. The rate may be ten to a thousand or more times as high for higher concentrations of more readily utilizable organic substances than ordinarily occur in lake or sea water. The complete oxidation of a milligram of a hexose (which may be regarded as a representative organic substance for purposes of calculating heat production) yields 3.7 calories. However, experiments on oxygen uptake and $CO_2$ formation indicate that only about half of the theoretical heat of combustion of such substances oxidized by bacteria is liberated as heat, the remainder being used in other vital reactions, including the synthesis of bacterial cell substance. Assuming that 40 per cent of the theoretical heat of combustion of substances oxidized by bacteria is dissipated as heat, we arrive at a value of $29.6 \times 10^{-12}$, or in round numbers $30 \times 10^{-12}$, calories liberated as heat per bacterial cell per hour.

Carlyle and Norman (1941) noted temperature increases ranging from 0.7 to 9.0°F. per hour in their experiments with decomposing straw in Dewar flasks. From their data on bacterial populations we calculate that their aerobic bacteria genrated heat at an average rate of $12 \times 10^{-7}$ calories per cell per hour.

### THERMOS FLASK EXPERIMENTS

Several gallons of mud from the lake were collected for experiments designed to measure microbial thermogenesis under carefully controlled conditions. Part of the mud was sterilized by autoclaving and the remainder of the raw mud was stored in a refrigerator until needed. Then, after permitting the mud to come to equilibrium with the temperature at which it was to be incubated, samples were dispersed in quart thermos flasks. Duplicate flasks of the sterilized mud were inoculated with one per cent by volume of raw mud. Following Norman *et al.* (1941), the thermos flasks filled with mud were incubated submerged in a water bath at a temperature approximating that of the mud in order to minimize heat losses. Temperatures were taken with long-stemmed mercury thermometers extending through one-hole stoppers, the bulb being submerged in the mud to a depth midway in the flask. The temperature of the mud was recorded at the onset of each experiment and after different periods of incubation. When incubated in a water bath maintained at 68.0±0.2°F., the temperature of mud containing active bacteria increased from one-half to a degree or more during 20 days (table 3).

TABLE 3.—*Temperature of Lake Mead mud samples after different periods of incubation in quart thermos flasks in a water bath at 68.0±0.2°F.*

| Description of mud | Temperature of mud after | | | Change in 20 days |
|---|---|---|---|---|
| | 0 days | 10 days | 20 days | |
| | °F. | °F. | °F. | °F. |
| Sterile mud (control) | 68.1 | 67.8 | 68.2 | +0.1 |
| Inoculated mud #1 | 68.5 | 68.6 | 69.1 | +0.6 |
| Inoculated mud #2 | 67.8 | 68.1 | 68.8 | +1.0 |
| Raw mud sample #1 | 68.0 | 68.4 | 69.4 | +1.4 |
| Raw mud sample #2 | 68.1 | 68.7 | 69.3 | +1.2 |

The experiment was repeated several times with various modifications, each of which demonstrated some slight degree of microbial thermogenesis. Although providing evidence of biochemical heating, the experiments have little quantitative significance because they do not duplicate conditions existing on the lake floor. Sampling disturbs the mud so that there is increased bacterial activity even at temperatures approximating conditions *in situ.* This may result in temporarily increased thermogenesis followed in stored mud by thermogenesis at a rate lower than on the lake floor, because oxidizable organic matter is consumed without being continuously replenished as it may be in the lake.

The influence of organic content on microbial thermogenesis was demonstrated by enriching mud samples with a chopped preparation of dried algae. The addition of 5 per cent by weight of the material resulted in temperature increases of six to ten degrees in mud incubated in aerated thermos flasks for five days at 68°F. Without aeration the temperature increase was only one or two degrees in five days.

### DISCUSSION

Biochemical oxygen demand (B.O.D.) tests on samples of Lake Mead mud collected from various depths showed little variation in the vertical distribution of biologically oxidizable organic matter, thereby indicating that most of the organic matter reaching the lake bottom must be oxidized in the topmost layers of mud. Ostensibly being oxidized about as rapidly as it reaches the lake bottom, utilizable organic matter does not accumulate to any appreciable extent, the 20-day B.O.D. values ranging from 247 to 479 parts per million. Significantly, it is at the mud-water interface where the thermocline is sharpest. Available evidence suggests that the temperature increase starting at the mud-water interface is attributable, at least in part, to microbial thermogenesis resulting from the oxidation of organic matter.

Presence of both utilizable organic matter and oxygen appear to be the most important factors affecting microbial thermogenesis. Heat was found to be generated much more rapidly in mud of high organic content through which oxygen was bubbled than in similar mud incubated under anaerobic conditions. Observations on the redox potential of samples from the lake indicated that free oxygen occurs only in the water and in the topmost layers of mud, below which anaerobic conditions prevail.

The microbial oxidation of cornmeal moistened with water in insulated Dewar flasks was found by James (1927) to result in temperature increases up to 9° under anaerobic conditions and as much as 64°F. when aerated with oxygen. Similarly aerated hay heated from an initial temperature of 86° to 143°F., and bacteria in aerated stable manure caused temperature increases exceeding 75°F. (James *et al.*, 1928). Carlyle and Norman (1941) observed biochemical heating in moist oat straw sufficient to cause temperature increases of nearly 90°F.

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## REFERENCES

Anderson, E. R., and Pritchard, D. W. (1951) Physical limnology of Lake Mead; Lake Mead sedimentation survey: U. S. Navy Electronics Laboratory, Report 258, 153 pp.

Carlyle, R. E., and Norman, A. G. (1941) Microbial thermogenesis in the decomposition of plant materials. Part II, Factors involved: Jour. Bacteriology, vol. 41, pp. 699–724.

Gilman, J. C., and Barron, D. H. (1930) Effect of molds on temperature of stored grain: Plant Physiology, vol. 5, pp. 565–573.

Gould, H. R. (1951) Some quantitative aspects of Lake Mead turbidity currents: Soc. Econ. Paleontologists and Mineralogists Special Pub. no. 2, pp. 34–52.

James, L. H. (1927) Studies in microbial thermogenesis. I, Apparatus: Science, vol. 65, pp. 504–506.

James, L. H., Rettger, L. F., and Thom, C. (1928) Microbial thermogenesis. II, Heat production in moist organic materials with special reference to the part played by microorganisms: Jour. Bacteriology, vol. 15, pp. 117–141.

Miehe, H. (1911) Über die Selbsterhitzung des Heues: Arb. deutsche landw. Gesell., vol. 196, pp. 1–36.

Norman, A. G., Richards, L. A., and Carlyle, R. E. (1941) Microbial thermogenesis in the decomposition of plant materials. Part I, An adiabatic fermentation apparatus: Jour. Bacteriology, vol. 41, pp. 689–698.

Wedberg, S. E., and Rettger, L. F. (1941) Factors influencing microbial thermogenesis: Jour. Bacteriology, vol. 41, pp. 725–743.

ZoBell, C. E. (1940a) Some factors which influence oxygen consumption by bactieria in lake water: Biol. Bull., vol. 78, pp. 388–402.

——— (1940b) The effect of oxygen tension on the rate of oxidation of organic matter in sea water by bacteria: Jour. Marine Research, vol. 3, pp. 211–223.

——— (1946) Marine microbiology. A monograph on hydrobacteriology: Chronica Botanica Co., Waltham, Mass., pp. 36–38.

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# 3. Wave Intensity Along a Refracted Ray [1,2]

By W. H. Munk [3] and R. S. Arthur [3]

is paper is concerned with the application of ray theory to the calculation of the sity of waves refracted in an arbitrary, two-dimensional velocity field, $c(x,y)$. y equation determines the path of the rays (orthogonals), and an equation of *ray ation* expresses the convergence or divergence along a ray. These two equations ombined into an equation of *wave intensity*, from which the intensity *along* a ray e determined given only the ray path and the wave velocity both on and near y. This procedure has advantages over the usual method of computing intensity measurements of the distance *between* adjacent rays.

plication is made to special types of velocity fields. It is demonstrated that lic convergences of rays with associated maxima of intensity occur along the axes rtain types of symmetrical underwater ridges (or of any comparable channel of num velocity). Along the axes of symmetrical underwater troughs the rays ge and the intensity diminishes exponentially. Numerical and graphical meth- r obtaining solutions over a complex bottom are outlined.

## 1. Introduction

served changes in the height of waves entering shallow water have accounted for on the basis of the change in group velocity and the t of refraction. For a wave train of given period the group velocity unction of depth only, and any variation in wave height along a fixed h contour is, therefore, the result of refraction. The *refraction* r, $K$, is a linear measure of this effect.

ave rays (or orthogonals) are defined as lines which are everywhere endicular to the wave fronts. They may be visualized as the wakes d surfboards which are always oriented normal to the crests, that is, e direction of wave motion. Let $l_0$ designate the distance between ent rays at some initial depth, $l$ the distance between the same rays arbitrary depth, and $\beta=l/l_0$ the *ray separation factor*. Then

$$K=|\beta|^{-\frac{1}{2}}, \quad K_b=|\beta|^{-\frac{1}{3}}, \tag{1.1}$$

nding on whether the arbitrary depth is outside or within the breaker (Munk and Traylor, 1947).

er a complex bottom, $\beta$ can be determined by graphical methods. technique (Hydrographic Office, 1944) consists of constructing the fronts by a method analogous to Huygen's and then drawing the Another method (Johnson, O'Brien, and Isaacs, 1948) makes it ble to draw rays immediately. In either method the refraction r is obtained by measuring the distance *between* adjacent rays. Here l be shown how the refraction factor *along* a ray can be determined

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directly. The latter procedure alone appears to be feasible in the ca of extreme convergence, such as occurs near focal points and causti (Pierson, 1951), or in the case of extreme divergence. However, the are precisely the conditions for which the approximations underlyi any of these methods, including ours, must be critically examined.

In the construction of refraction diagrams it is assumed that t expression

$$c^2=\frac{g}{k}\tanh kh$$

for the velocity $c$ of a wave of length $2\pi/k$ at constant depth $h$ is adequate approximation in the case of sloping bottoms. This assumpti is supported by observations as well as theoretical investigations of certa special cases (Lewy, 1946; Stoker, 1947; Lowell, 1949). The comput tion of intensity from these refraction diagrams is based on ray theo For very shallow water Lowell (1949) has shown this procedure to justified, except in regions of strong convergence or divergence of ra No attempt to justify ray theory is intended in the development th follows.

## 2. The Ray Equation

Starting from Fermat's principle, according to which the ray is a pa of minimum travel time, it can be shown that the expressions for pa metric representation of the ray, $x=x(t)$ and $y=y(t)$, satisfy the equatio

$$\frac{dx}{dt}=c\cos\alpha;\quad \frac{dy}{dt}=c\sin\alpha;\quad \frac{d\alpha}{dt}=-\frac{Dc}{Dn}, \qquad \text{(2.1a,b,}$$

where $t$ is the travel time, $\alpha$ the angle between the ray and the $x$-axis, a $D/Dn$ denotes differentiation with respect to arc length $n$ along the wa front (fig. 1). The derivation of eq 2.1 requires that the wave velocit $c$, be a *given* function of $x,y$ which, along with the necessary partial deri tives, is continuous. An even more general form of eq 2.1 is valid f waves refracted in the presence of a current as long as the conditions o obtain (Arrow, 1949; Arthur, 1950).

Elimination of $\alpha$ from eq 2.1a,b yields

$$dt=(1/c)\sqrt{(dx)^2+(dy)^2}=(1/c)Ds,$$

where $s$ is the arc length along the ray. Substitution in eq 2.1c gives t ray equation[4]

$$\frac{D\alpha}{Ds}=-\frac{1}{c}\frac{Dc}{Dn}, \qquad \text{(2.}$$

which states that the curvature of the ray is equal to the logarithn velocity gradient along the wave front and that the ray bends towa the direction of lower velocity.

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[4] Equation 2.2 can be derived directly from the eikonal equation, which is the fundamental equatio the wave fronts. Frank, Bergmann, and Yaspan (1946, pp. 42–46) give a complete development. Eq tion 2.2 follows immediately from eq 22 of their paper when specialized to two dimensions. See a eq 3.5 of Lowell (1949, p. 283), which is identical with eq 2.2.

## 3. The Equation of Ray Separation

he variation of $\beta$ in terms of the arc length $s$ along a ray is derived n elementary considerations using figure 1. If $\alpha$ denotes the angle ween the ray and the $x$-axis at point $P$, the corresponding angle of a through $A$, an infinitesimal distance $l$ removed, is $\alpha+D\alpha$, where

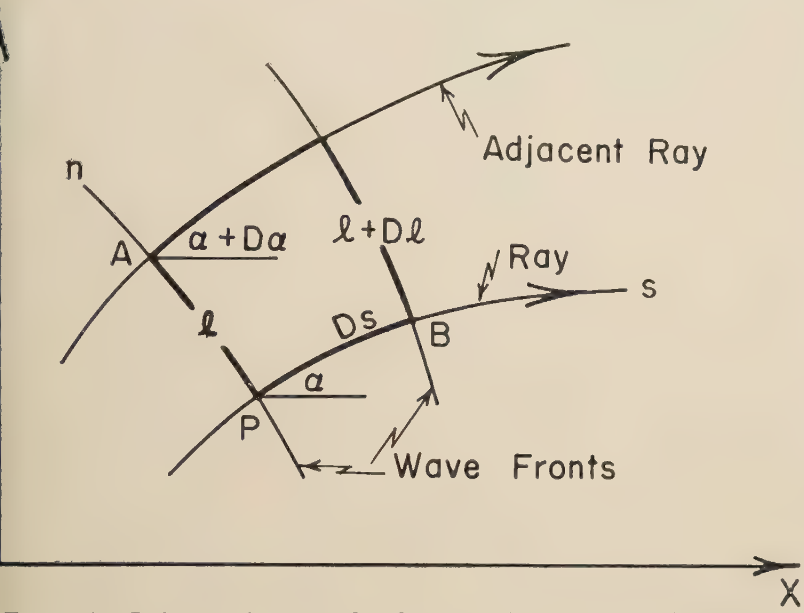

FIGURE 1. *Definition of terms used in derivation of ray equation and equation of ray separation.*

$=(D\alpha/Dn)l$. The ray separation at $B$ is $l+Dl$, where $Dl=D\alpha\cdot Ds$. nce

$$\frac{1}{l}\frac{Dl}{Ds}=\frac{D\alpha}{Dn}. \tag{3.1}$$

erms of $\beta=l/l_0$, the equation of ray separation

$$\frac{1}{\beta}\frac{D\beta}{Ds}=\frac{D\alpha}{Dn} \tag{3.2}$$

otained. According to eq 3.2 the logarithmic change in the separation or along the way is equal to the curvature of the wave front. Lowell 19, p. 286) has derived this equation in a more systematic manner, g the Gauss integral theorem.

t is to be emphasized that differentiation with respect to arc length $s$ $n$ is accomplished by use of the special operators

$$\frac{D}{Ds}=(\cos\alpha)\frac{\partial}{\partial x}+(\sin\alpha)\frac{\partial}{\partial y},$$

$$\frac{D}{Dn}=-(\sin\alpha)\frac{\partial}{\partial x}+(\cos\alpha)\frac{\partial}{\partial y}. \tag{3.3a,b}$$

The arc lengths $s$ and $n$ do not constitute a set of curvilinear coordinate
If a set of curvilinear coordinates $r$ for the rays and $w$ for the wave fron
were to be introduced, a more complete notation would be

$$(\partial/\partial s)_r \text{ for } D/D_s, \text{ and } (\partial/\partial n)_w \text{ for } D/Dn.$$

It is useful to derive a modified version of the ray-separation equati
by eliminating $\alpha$ from the ray eq 2.2 and the ray separation eq 3.
Because the operators 3.3 involve $\alpha$, which varies differently along ray ar
wave front, the order of differentiation is not immaterial in the mix
second derivatives. For example, the difference of the mixed secon
derivatives of $\alpha$, as computed from repeated use of eq 3.3 is not zero b

$$\frac{D}{Dn}\left(\frac{D\alpha}{Ds}\right)-\frac{D}{Ds}\left(\frac{D\alpha}{Dn}\right)=\left(\frac{\partial\alpha}{\partial x}\right)^2+\left(\frac{\partial\alpha}{\partial y}\right)^2=\left(\frac{D\alpha}{Ds}\right)^2+\left(\frac{D\alpha}{Dn}\right)^2. \tag*{(3.}$$

Substitution from eq 2.2 and 3.2 gives

$$\frac{D}{Dn}\left(\frac{D\alpha}{Ds}\right)-\frac{D}{Ds}\left(\frac{D\alpha}{Dn}\right)=\frac{1}{c^2}\left(\frac{Dc}{Dn}\right)^2+\frac{1}{\beta^2}\left(\frac{D\beta}{Ds}\right)^2. \tag*{(3.}$$

Differentiating eq 2.2 and 3.2 with respect to $s$ and $n$, respectively, ar
adding, yields

$$\frac{D}{Dn}\left(\frac{D\alpha}{Ds}\right)-\frac{D}{Ds}\left(\frac{D\alpha}{Dn}\right)=-\frac{1}{c}\frac{D^2c}{Dn^2}+\frac{1}{c^2}\left(\frac{Dc}{Dn}\right)^2-\frac{1}{\beta}\frac{D^2\beta}{Ds^2}+\frac{1}{\beta^2}\left(\frac{D\beta}{Ds}\right)^2. \tag*{(3.}$$

If the right-hand members of eq 3.5 and 3.6 are equated, the eliminati
of $\alpha$ from eq 2.2 and 3.2 is completed, and the final result is the modifi
equation of ray separation,

$$\frac{D^2\beta}{Ds^2}+k^2\beta=0, \tag*{(3.}$$

where

$$k^2=\frac{1}{c}\frac{D^2}{Dn^2}. \tag*{(3.}$$

Equation 3.7 relates changes in the ray separation factor along the r
to changes in wave velocity along the wave front. The solution $\beta$(
to this second-order equation involves two arbitrary constants that c
be evaluated in terms of the initial conditions $\beta=\beta_0$ and $D\beta/Ds=K$
at $s=0$. Here

$$\frac{1}{\beta}\frac{D\beta}{Ds}=\frac{D\alpha}{Dn}=\kappa \tag*{(3.}$$

represents the curvature of the wave front, which is taken positive if t
wave front is convex as viewed from the direction of increasing $s$.

Either form of the equation of ray separation contains in a compa
manner the law governing the variation of intensity in a two-dimensio
velocity field, according to ray optics. The simplicity of eq 3.2 and
is, however, somewhat misleading. Their application involves the c

ction of wave fronts[5] and rays on the refraction diagram, but it is rable to construct only rays. We shall therefore derive an equation ave intensity that is less compact but better adapted to calculations. equation of wave intensity will eliminate the need for constructing wave fronts, and will allow the determination of $\beta$ given only a ray and the wave velocity everywhere, i.e., both on and near the ray.

## 4. Derivation of an Equation of Wave Intensity

ifferentiation of $c$ with respect to $n$ gives

$$\frac{Dc}{Dn} = -(\sin\alpha)\frac{\partial c}{\partial x} + (\cos\alpha)\frac{\partial c}{\partial y}, \qquad (4.1)$$

$$= -(\sin\alpha)\left\{-(\sin\alpha)\frac{\partial^2 c}{\partial x^2} - \left[(\cos\alpha)\frac{\partial c}{\partial x} + (\sin\alpha)\frac{\partial c}{\partial y}\right]\frac{\partial\alpha}{\partial x} + (\cos\alpha)\frac{\partial^2 c}{\partial x\partial y}\right\}$$

$$(\cos\alpha)\left\{(\cos\alpha)\frac{\partial^2 c}{\partial y^2} - \left[(\cos\alpha)\frac{\partial c}{\partial x} + (\sin\alpha)\frac{\partial c}{\partial y}\right]\frac{\partial\alpha}{\partial y} - (\sin\alpha)\frac{\partial^2 c}{\partial x\partial y}\right\}. \qquad (4.2)$$

q 4.2 is simplified and substitutions are made for groups of terms equal $c/Ds$ and $D\alpha/Dn$, the result is

$$\frac{1}{c}\frac{D^2 c}{Dn^2} = \frac{1}{c}\left[\sin^2\alpha)\frac{\partial^2 c}{\partial x^2} - 2(\sin\alpha\cos\alpha)\frac{\partial^2 c}{\partial x\partial y} + (\cos^2\alpha)\frac{\partial^2 c}{\partial y^2} - \frac{Dc}{Ds}\frac{D\alpha}{Dn}\right]. \qquad (4.3)$$

term $D\alpha/Dn$, the curvature of the wave front, cannot be evaluated, n only the ray path and $c=c(x,y)$. However, the equation of ray ration 3.2 shows that

$$\frac{D\alpha}{Dn} = \frac{1}{\beta}\frac{D\beta}{Ds},$$

this result, together with eq 4.3 and 3.8, gives an equation of wave nsity

$$\frac{D^2\beta}{Ds^2} + p\frac{D\beta}{Ds} + q\beta = 0, \qquad (4.4)$$

re

$$= -(\cos\alpha)\left[\frac{1}{c}\frac{\partial c}{\partial x}\right] - (\sin\alpha)\left[\frac{1}{c}\frac{\partial c}{\partial y}\right],$$

$$= (\sin^2\alpha)\left[\frac{1}{c}\frac{\partial^2 c}{\partial x^2}\right] - 2(\sin\alpha\cos\alpha)\left[\frac{1}{c}\frac{\partial^2 c}{\partial x\partial y}\right] + (\cos^2\alpha)\left[\frac{1}{c}\frac{\partial^2 c}{\partial y^2}\right]. \qquad (4.5a,b)$$

s indicated, the coefficients $p$ and $q$ in eq 4.5 are functions of the arc th $s$ along a ray only, and the wave fronts are not required for their uation. Equation 4.4 offers, therefore, a practical basis for the rmination of wave intensity, and considering the high development

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eq 3.2 the curvature of the wave front enters explicitly; in eq 3.7 the evaluation of $k^2$ at a point on y involves the second derivative of $c$ along the curvilinear wave front. One may think that a ent approximation could be attained by evaluating the derivative along a straight-line tangent to ave front, but it is easy to select examples that show that this is not the case.

of ray optics, it is surprising that this equation is not familiar. An explanation might be that this law governing-wave intensity is adapted to a continuous velocity field, whereas the development of ray optics has been primarily concerned with discontinuous changes involved in the design of lens systems.

The quantities in square brackets depend on $c$ and its partial derivatives with respect to the fixed coordinates $x,y$. The values of $p$ and $q$ are readily determined at each point of the ray in terms of a local coordinate system that has its origin on the ray at the point of determination and some specified orientation at that point. Two obvious, special cases

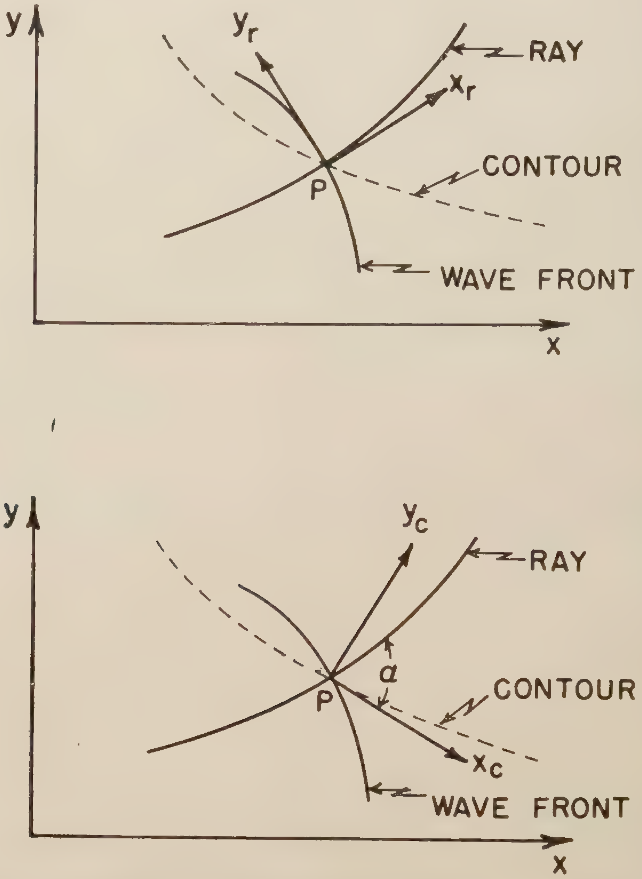


FIGURE 2. *Local coordinate systems oriented with respect to ray and depth contours.*

are a system $(x_r,y_r)$ oriented with respect to the rays (fig. 2, upper) and a system $(x_c,y_c)$ oriented with respect to the contours (fig. 2, lower).

For the ray system, $\alpha=0$ and

$$p(s)=-\frac{1}{c}\frac{\partial c}{\partial x_r},$$

$$q(s)=\frac{1}{c}\frac{\partial^2 c}{\partial y_r^2}. \tag{4.5c,d}$$

ne contour system, $\partial c/\partial x_c=0$ and $\partial^2 c/\partial x_c^2=-\kappa_c(\partial c/\partial y_c)$, where he curvature of the contour at the point of intersection with the Consequently,

$$-(\sin\alpha)\left[\frac{1}{c}\frac{\partial c}{\partial y_c}\right],$$

$$(\cos^2\alpha)\left[\frac{1}{c}\frac{\partial^2 c}{\partial y_c^2}\right]-2(\sin\alpha\cos\alpha)\left[\frac{1}{c}\frac{\partial^2 c}{\partial x_c\partial y_c}\right]-(\sin^2\alpha)\left[\frac{\kappa c}{c}\frac{\partial c}{\partial y_c}\right]\cdot \quad (4.5e,f)$$

ms 4.5c,d appear to be simpler. However, a possible advantage of 4.5e,f is that the expressions in square brackets depend only on rties of the depth contours, and can be tabulated on charts of n topography along each contour, regardless of direction of wave ach, providing the wave period is specified. The dependence on ion enters entirely through the trigonometric functions of $\alpha$ in arentheses. Equation 4.5f is simplified if the contours are parallel ve at most only slight convergence or divergence, for, then $|\partial^2 c/$ $|\ll 1$, and the middle term is negligible.

## 5. Application to Special Types of Underwater Topography

### 5.1 Shelf of Uniform Depth

the depth is constant, $c$ is constant and $p$ and $q$ are zero. The ion of wave intensity, 4.4, reduces to

$$\frac{D^2\beta}{Ds^2}=0, \quad (5.1)$$

solution

$$\beta=\beta_0(\kappa_0 s+1). \quad (5.2)$$

two constants of integration (section 3) are evaluated in terms of nitial value, $\beta_0$, of the ray separation factor and the initial curvature, the wave front at the edge of the shelf, where $s=0$.

e depth being constant, there is no refraction over the shelf and the are straight. However, $\beta$ remains constant along the ray only if the front is initially plane ($\kappa_0=0$). If the wave front is initially convex rging rays) as viewed from the positive $s$ direction, then $\kappa_0>0$ and $\beta$ ases linearly with $s$ along the ray. The refraction factor 1.1 and intensity decrease. If the wave front is initially concave (conng rays), then $\kappa_0<0$ and $\beta=0$, where $s=-1/\kappa_0$. Therefore, at a nce $(-1/\kappa_0)$ along the ray the wave intensity becomes infinite on asis of ray theory, i.e., a focal point, or caustic, is reached. This usion is in agreement with results obtained by Pierson (1951) in a led analysis of refraction over a semicircular ledge.

### 5.2 Straight, Parallel Contours

the contours are parallel to the $x$-axis, then $c=c(y)$ and $\alpha=\alpha(y)$; quation of wave intensity, 4.4, reduces to

$$\frac{D^2\beta}{Ds^2}-(\sin\alpha)\left[\frac{1}{c}\frac{dc}{dy}\right]\frac{D\beta}{Ds}+(\cos^2\alpha)\left[\frac{1}{c}\frac{d^2c}{dy^2}\right]\beta=0. \quad (5.3)$$

The known refraction relationships for this case, in terms of α, (Hydrographic Office, 1944)

$$\left.\begin{aligned} \frac{c}{c_0}&=\frac{\cos\alpha}{\cos\alpha_0},\\ \beta=\frac{l}{l_0}&=\frac{\sin\alpha}{\sin\alpha_0}.\end{aligned}\right\} \qquad \text{(5.4}$$

The first relation is Snell's law. It can be verified that the sec relation satisfies eq 5.3, but the details are tedious and uninteresting.

## 5.3 Ridge and Trough

It is instructive to consider in some detail the special cases of a ri or trough for which the contours are symmetrical with respect to a strai axis. One ray is assumed to coincide initially with the axis, and eq shows that this ray continues as a straight line. The variation in β al this axial ray is to be determined. The application to wave refract along any channel of maximum or minimum velocity, e.g., the so channel, is obvious.

Let the $x$-axis coincide with the axial ray and be directed in the direct of wave propagation. Since $\alpha=0$, then $D/Ds=d/dx$ and the coefficie of the equation of wave intensity, 4.4, are

$$\left.\begin{aligned} p(x)&=-\left(\frac{1}{c}\frac{\partial c}{\partial x}\right)_{y=0}=2a,\\ q(x)&=\left(\frac{1}{c}\frac{\partial^2 c}{\partial y^2}\right)_{y=0}=b^2,\end{aligned}\right\} \qquad \text{(5.5}$$

where $a$, which is dependent on the inclination of the ridge or tro along the axis, and $b^2$, which is dependent on the bottom curvature nor to the axis, are assumed constant along the axial ray. Along the a ray the wave velocity, as determined by eq 5.5a, is

$$c/c_0=e^{-2ax}, \qquad \text{(}$$

where $c_0$ is the value of $c$ at $x=0$. If $a=0$, the wave velocity and de along the axis are constant, and the ridge or trough is level. More g erally, the ridge or trough may be inclined upward ($a>0$) or downw ($a<0$) in the direction of the axis. From eq 5.5b it is apparent that a ridge $b^2>0$ and for a trough $b^2<0$.

The resulting form of the modified equation of wave intensity is

$$\frac{d^2\beta}{dx^2}+2a\frac{d\beta}{dx}+b^2\beta=0, \qquad \text{(}$$

a second-order, linear differential equation with constant coefficie The solution in its various forms is particularly familiar because the sa type of equation arises in the study of damped oscillatory systems. ' solutions corresponding to overdamped, critically damped, and un ed oscillations are, respectively,

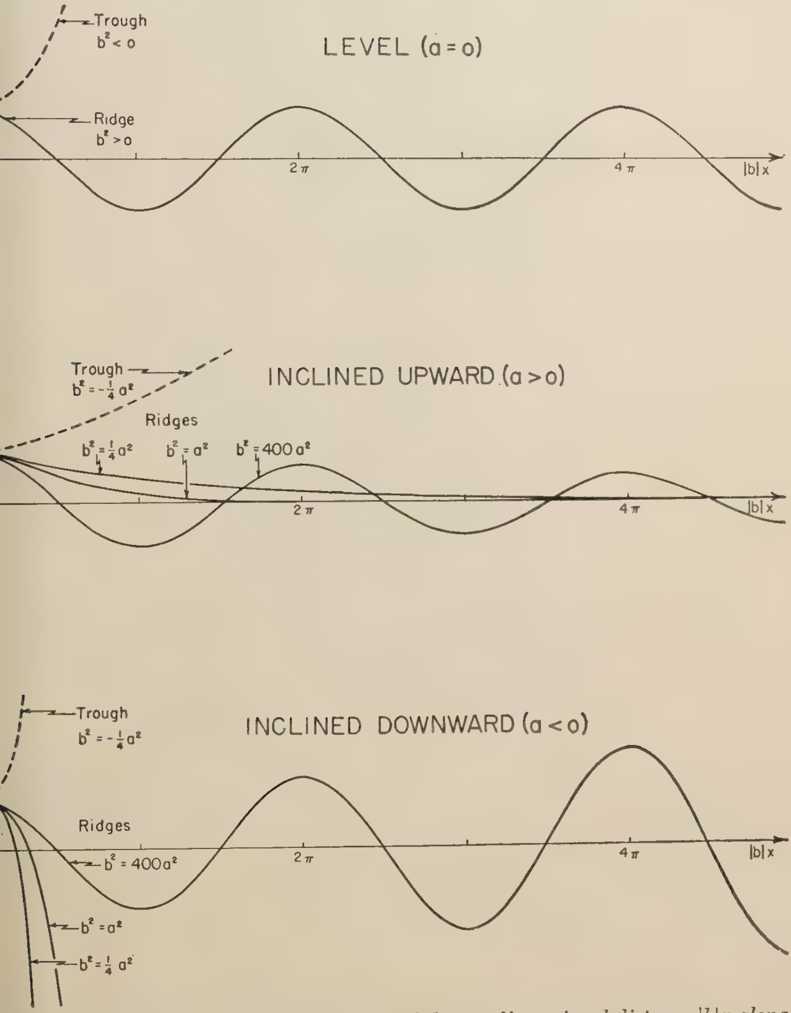
$$=\beta_0 e^{-ax}\left[\cosh(\lambda x)+\left(\frac{a+\kappa_0}{\lambda}\right)\sinh(\lambda x)\right] \quad \text{for} \quad \lambda^2>0,$$

$$=\beta_0 e^{-ax}[1+(a+\kappa_0)x] \quad \text{for} \quad \lambda^2=0, \qquad (5.8\text{a,b,c})$$

$$=\beta_0 e^{-ax}\left[\cos(i\lambda x)+\left(\frac{a+\kappa_0}{i\lambda}\right)\sin(i\lambda x)\right] \quad \text{for} \quad \lambda^2<0,$$

$\lambda^2=a^2-b^2$. All arguments are real. The two constants of integra-
ave been evaluated from the initial conditions (section 3) at
$3=\beta_0$ and $(d\beta/dx)_0=\kappa_0\beta_0$, where $\kappa_0$ is the initial curvature of the
front. For waves from a distant storm, $\kappa_0 \doteq 0$.

e various forms of the solutions are shown in figure 3. The simplest
s that of a level ridge or trough (fig. 3, upper). The results can be



e 3. *The separation factor $\beta$ as function of the nondimensional distance $|b|x$ along*
*he axes of symmetrical ridges ($b^2>0$) and troughs ($b^2<0$), where $|b|=$mod b.*

visualized easily in terms of Eckart's (1950) analogy between the ra
and the paths of small balls rolling along suitably shaped surfaces wi
"inverse" bottom topography (fig. 4). The ray over the submari
ridge corresponds to the path of a ball rolling along a trough. If slight
disturbed, the ball will roll first somewhat to one side and then to t
other side of the trough bottom, crossing the bottom at distances $\pi/$
The zeroes of the $\beta$ solution occur where the paths converge periodical
to produce a focal point or a caustic with infinite wave intensity.[6] T

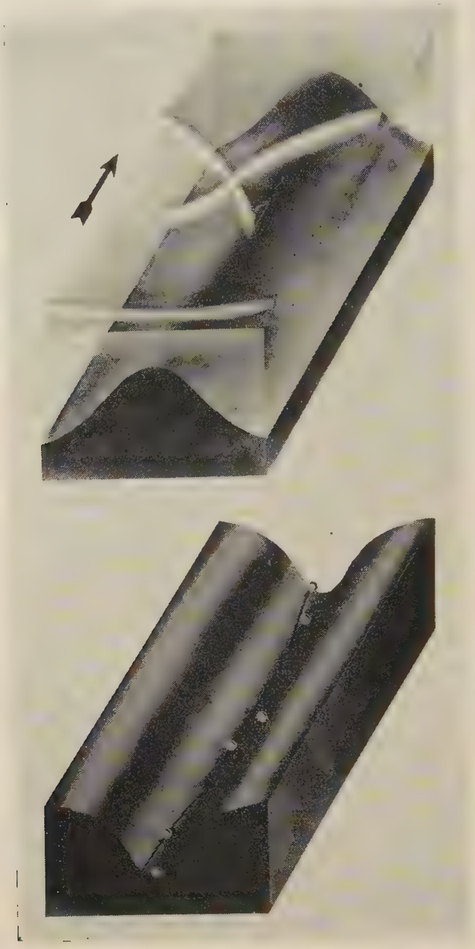


FIGURE 4. *Schematic view of wave refraction over a level, underwater ridge (upp and the corresponding rays traced by small balls rolling along a surface of "inve topography (lower).*

ray over the trough, on the other hand, corresponds to the path of a
moving along the very crest of a ridge. If slightly displaced, it will
down one side or the other. The adjacent rays, therefore, diverge f
the axial ray and the wave intensity diminishes.

---

[6] Allyn Vine of the Woods Hole Oceanographic Institution has called our attention to an unpubl manuscript by F. Brooks (1948) in which there is derived the distance $\pi/b$ between focal points on th of a sound channel where the velocity varies parabolically with depth.

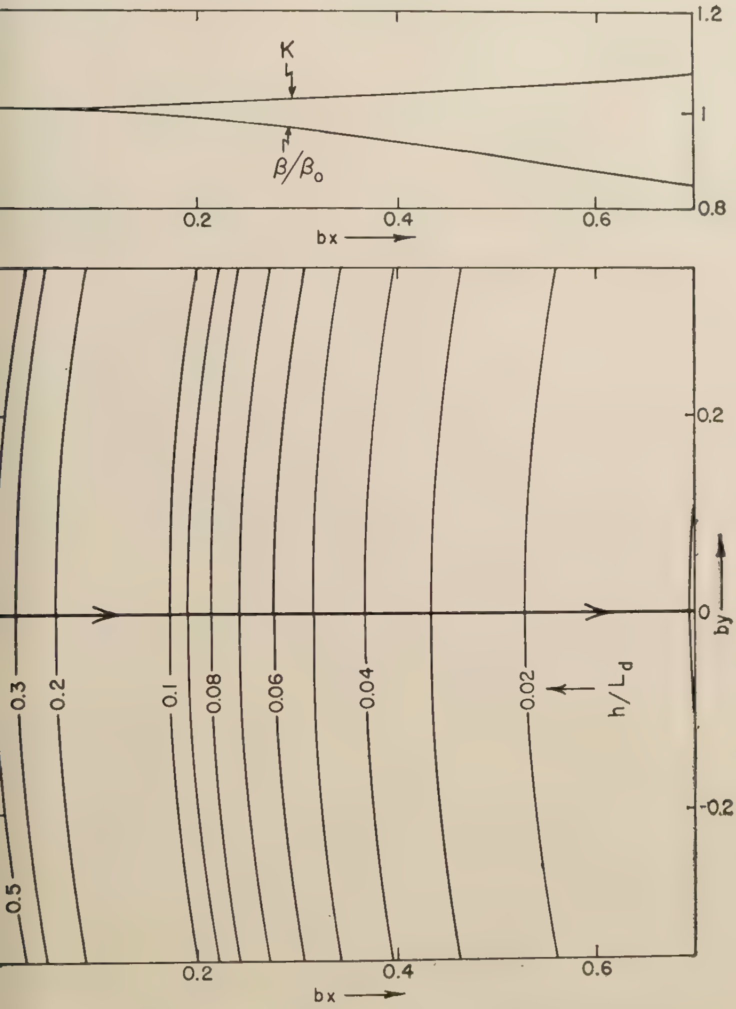
g ridges have periodic convergences only if the lower sign holds nequality $a^2 \gtreqless b^2$. This condition stated in terms of the curvature ontours, 4.5e,f, becomes

$$\left(\frac{1}{c}\frac{\partial c}{\partial x}\right)^2 \gtreqless (4\kappa_c)^2. \qquad (5.9)$$

ical case arises when the two members of the inequality are equal . Setting

$$c/c_d = e^{-2ax}\cosh ay, \qquad (5.10)$$

is the deep-water wave velocity, leads to the critical case. dimensional representation of the topography (see fig. 5) asso- ith eq 5.10 indicates that the "critical" ridge has a steep inclina-



*An example of a submarine ridge corresponding to the "critically damped" case.*

tion and is relatively broad (contours have small curvature). I inclination is less steep, periodic focal points, or caustics, occur alon axial ray.

## 6. Application to a Complex Bottom

It is assumed that the rays have been constructed directly (Joh O'Brien, and Isaacs, 1948) and that $p$ and $q$ along the rays have evaluated from the contour charts by some suitable method. methods will be discussed in a forthcoming paper. It suffices to re here that neither the term $p(s)D\beta/Ds$ or $q(s)\beta$ in the modified equ of wave intensity

$$\frac{D^2\beta}{Ds^2}+p(s)\frac{D\beta}{Ds}+q(s)\beta=0$$

may, in general, be considered negligible, and to outline the follo approximate methods for solution of the complete equation.

### 6.1 Constant Values of p and q

If the ray is divided into small intervals, and $p(s)$, $q(s)$ are replac average values within each interval, the solution appropriate to interval is of the trigonometric or hyperbolic form discussed in se 5.3. The solutions are joined together by requiring $\beta(s)$ and $D\beta/Ds$ continuous from one interval to the next.

### 6.2 Kelvin's Method

This method involves approximating the integral curve of a se order differential equation by fitting together circular arcs (W 1948). Johnson, O'Brien, and Isaacs (1948) have derived an esser similar technique for the construction of wave rays. Consider th struction of the integral curve $\beta=\beta(s)$ on a $\beta,s$-diagram, wher curvilinear coordinate $s$ is now laid out rectilinearly. If the angle be the integral curve and the $s$-axis is $\theta$, then the slope of the curve is $D\beta$ tan $\theta$, and the curvature, using eq 4.4, is

$$\kappa_\beta=\frac{D^2\beta/Ds^2}{[1+(D\beta/Ds)^2]^{3/2}}=-(p\tan\theta-q\beta)\cos^3\theta.$$

The curvature is computed at the initial point $s=0$, where $\beta$, $p$, and $q$ are all known. The curvature is assumed constant over a interval of $s$, and an arc of a circle of this curvature constructed fro initial point with the proper initial slope. The values of $\beta$ and $D\beta$, the end of the small interval are obtained, a new curvature com and the new arc laid off, keeping $\beta$ and $D\beta/Ds$ continuous. Repe of the process produces an approximation to the integral curve $\beta$= This method has the advantage of employing similar procedur computing the ray and the intensity.

### 6.3 WKB Method

The transformation

$$\beta=v(s)e^{-\frac{1}{2}\int pDs}$$

the equation of wave intensity 4.4 to the normalized form

$$\frac{D^2v}{Ds^2}-\mu^2v=0, \tag{6.3}$$

$$\mu^2(s)=q-\frac{1}{4}p^2-\frac{1}{2}\frac{Dp}{Ds}. \tag{6.4}$$

tion 6.3 has been studied intensively in quantum mechanics, and ssible to adapt, with certain modifications, methods which have eveloped for finding approximate solutions (see, for example, and Morse, 1929, pp. 44-47, 111–114). An approximate solution, onstitutes the basis of the WKB method is,

$$\sqrt{\frac{\mu_0}{\mu}}\left\{A\exp\left[-\int\left(\frac{1}{2}p+i\mu\right)Ds\right]+B\exp\left[-\int\left(\frac{1}{2}p-i\mu\right)Ds\right]\right\}, \tag{6.5}$$

$_0$ is the value of $\mu$ at $s=0$, and the arbitrary constants $A$ and $B$ be evaluated from the initial conditions. The solution is trigoic for $\mu^2>0$ and hyperbolic for $\mu^2<0$. The approximation becomes ate when $\mu^2$ approaches zero, and through these "forbidden" solutions of type 6.5 have to be joined to other special solutions.

### 6.4 Analogue Computers

modified equation of wave intensity is analogous to the equation amped oscillation. It is also analogous to the equation of an ory voltage, $V$, in a $RLC$ circuit, provided we identify $p$ with nd $q$ with $1/LC$, $\beta$ with $V$, and $s$ with time. By changing resistance pacitance with time in the required manner, the recorded voltage give the desired solution. A more useful analogy is probably that telegraph equation. Bullard and Moon (1931) have discussed a l which depends on the equations of motion of a current-carrying spended in a magnetic field. Mechanical analogue computers, s the differential analyzer, can also be used to obtain the solution. erical methods which are capable of greater accuracy than any of ove outlined methods are available (Willers, 1948; Kamke, 1943). r precision is hardly warranted, however, in view of the fact that the topography is known only approximately and that ray theory is only an approximate method for determining wave intensity.

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Carl Eckart of the Marine Physical Laboratory; Dr. Sherman C. of the Office of Naval Research, London; and Dr. Willard J. , Jr. of the Department of Meteorology, New York University, ade many helpful comments. Dr. Pierson has undertaken experiin a ripple tank for the purpose of checking the applicability of our ory results for underwater troughs and ridges. He will report his sions at a later date.

## 7. References

[1] Arrow, Kenneth J., 1949, On the use of winds in flight planning, J. Met. **6**, 150-

[2] Arthur, Robert S., 1950, Refraction of shallow water waves. . . . Trans., A
Geophy. Union, **31**, 549–552.

[3] Bullard, E. C., and Moon, P. B., 1931, A mechanical method for the solutio
second-order linear differential equations. Proc. Cambr. Phil. Soc. **27**, 546-

[4] Condon, Edward U., and Morse, Phillip M., 1929, Quantum Mechanics.
York, McGraw-Hill.

[5] Eckart, Carl, 1950, The ray-particle analogy. J. Mar. Research **9**, 139–144.

[6] Frank P. G., Bergmann, P. G., Yaspan, A., 1946, Ray acoustics (Chap.
Physics of sound in the sea), NDRC Summary Tech. Rep., Div. 6, **8**.

[7] Hydrographic Office, 1944. Breakers and surf. Hydrographic Off., Navy D
Pub. No. 234.

[8] Johnson, J. W., O'Brien, M. P., Isaacs, J. D., 1948, Graphical constructio
wave refraction diagrams. Hydrographic Off., Navy Dept., Pub. No. 605.

[9] Kamke, E., 1943, Differentialgleichungen Lösungsmethoden und Lösun
Leipzig, Akad. Verlagsgesellsch. . . . v. 1.

[10] Lewy, H., 1946, Water waves on sloping beaches. Bul. Amer. Math. Soc.
737–775.

[11] Lowell, Sherman Cabot, 1949, The propagation of waves in shallow w
Comm. on Pure and App. Math. **2**, 275–291.

[12] Munk, W. H., and Traylor, M. A., 1947, Refraction of ocean waves . . . J. Geol
1–26.

[13] Pierson, Willard J., Jr., 1951, The interpretation of crossed orthogonals in
refraction phenomena. Tech. Memo. No. 21, Beach Erosion Board, Corp
Engin.

[14] Stoker, J. J., 1947, Surface waves in water of variable depth. Quart. of
Math. **5**, 1–54.

[15] Willers, Fr. A., 1948, Practical Analysis, New York, Dover.

REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. VII
SEDIMENT CORES FROM THE NORTH ATLANTIC OCEAN. NO. 1

# NORTH ATLANTIC FORAMINIFERA

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## Contents

Page
Summary . . . . . 3
Introduction . . . . . 4
Locations of Stations . . . . . 5
Method of Study . . . . . 6
The Foraminifera Species . . . . . 10
  Planktonic Species . . . . . 10
  Benthonic Species . . . . . 23
Planktonic Foraminifera in Surface Sediment Samples . . . . . 50
  Distribution . . . . . 50
  Discussion . . . . . 70
Distribution of Foraminifera in the Cores . . . . . 73
  Description of Core Faunas . . . . . 73
  Interpretation of Core Faunas . . . . . 108
    Recognition of Faunal Sequences . . . . . 108
    Mixed Planktonic Faunas . . . . . 108
    Displaced Faunas. . . . . . 109
    Fossil Faunas . . . . . 110
    Correlation of Faunas . . . . . 111
Observations on Solution of Calcium Carbonate . . . . . 117
Summary Discussion . . . . . 119
References . . . . . 121

## Summary

Foraminifera have been studied from 39 long deep-sea cores collected from low and mid latitudes in the North Atlantic. Modern Foraminifera populations have been studied from 53 undisturbed surface sediment samples collected with a short coring tube. Thirty planktonic species of Foraminifera and 123 species of benthonic Foraminifera are discussed and illustrated. Four of the benthonic species are described as new.

The deep-sea benthonic species are widely distributed in the cores indicating that the conditions influencing them on the ocean floor are essentially uniform.

The following distributions of planktonic species have been ascertained from the study of surface sediment samples:

a. Species characteristic of low latitudes, less than 20° N Lat.: *Globorotalia menardii*, *G. tumida* and *Pulleniatina obliquiloculata*.

b. Species which occur in greater abundance in low latitudes than in mid latitudes, although they occur at most stations: *Globigerina eggeri* and *Globigerinoides sacculifera*.

c. *Globigerina pachyderma* is confined to high and mid latitudes.

d. Species which are more abundant in mid latitudes but also occur in low latitudes: *Globigerina bulloides*, *G. inflata*, *Globorotalia hirsuta*, *G. scitula* and *G. truncatulinoides*.

e. Species universally distributed in the samples: *Globigerinella aequilateralis*, *Globigerinita glutinata*, *Globigerinoides*

*conglobata*, *G. rubra* and *Orbulina universa*.

These distributions are tentatively correlated with distributions of sea surface isotherms.

4. The long cores contain layers of faunas normal for their latitudes alternating with faunas typical of a higher latitude. These are interpreted as representing alternating »warm» and »cold» epochs, and while a possible Pleistocene age is suggested for some of these, others are probably pre-Pleistocene. Correlation of these epochs appears possible in the mid-latitude cores, and may be possible elsewhere.

   A southward migration of the surface isotherms is indicated when the higher-latitude faunas were deposited; these faunal data also indicate that the tropical areas were cooler than at present.

5. Several cores contain shallow-water benthonic Foraminifera which have been displaced from shallow water. These are located relatively near areas of high submarine relief, such as islands and the coast of South America. These displaced faunas are associated with layers of sand. It is suggested that much of the mud in the deep ocean may be the finer fraction of sediments displaced from shoaler water.

6. Several fossil species are recorded from four cores; these fossils are believed to be Miocene in age. It is suggested that in two of these cores there has been more or less continuous deposition since the late Miocene.

7. *Globorotalia tumida* (*sensu strictu*) appears to extend back only to the last »cold» epoch, which is interpreted as late Pleistocene in age.

8. There is abundant evidence of the solution of the calcium carbonate of the Foraminifera tests in many samples, indicated by solution associated with broken specimens. Some species appear to be more resistant to solution than others and may remain where others have been destroyed. Benthonic species appear to be especially resistant to solution. The most intensive solution effects are seen in surface sediment samples from water depths greater than about 5 000 m., but there are exceptions: a large population is recorded from 7 500 m.

   Some cores have layers of broken specimens alternating with layers showing no evidence of solution. It is suggested that most solution may have occurred at the surface of the sediment and that variation in amount of solution is in part due to differences in rate of production of calcareous Foraminifera.

9. A mixed low- and mid-latitude modern planktonic fauna off Africa between approximately 15° and 20° N Lat. is attributed to mixing of tropical and mid-latitude water masses at the convergence of the Equatorial Counter Current and the Canaries Current. Mixed planktonic faunas are recognized from lower sections in cores off Africa between approximately 0° and 7° N Lat. This suggests that the convergence area has moved southward at various times during the past.

10. There appear to be marked differences in rate of deposition of sediment from place to place and time to time, according to the evidence from these cores.

## Introduction

The development of the piston coring tube by Kullenberg (1947) has been an important advance in the study of sediments from the deep sea. This instrument obtains core samples which are consistently 10 to 15 m. long, and occasionally more than 19 m. long; whereas, the length of previous marine cores seldom has exceeded 3 or 4 m. Collection of such relatively thick cross-sections of deep-sea sediment has increased the possibility of study of the recent history of the deep ocean basins, during the late, and possibly early, Tertiary.

This is one of several papers reporting on various aspects of the long submarine cores collected by the Swedish Deep Sea Expedition. The Foraminifera populations in 39 of the long cores collected from the Atlantic are reported. In addition, the Foraminifera populations in 53 samples of surface sediment from the North Atlantic have been analyzed.

Foraminifera have been demonstrated to be of considerable value in studying problems of paleoceanography. They are delicately adjusted to the various marine environments and they occur in considerable abundance in all parts of the oceans. They can be used to decipher environments of the geologic past if we know their ecologic distributions in the modern faunas and if it is assumed that the ecological adjustments were essentially similar during the past. There is relatively little reliable information on the ecology of this group, but there is sufficient to suggest certain broad relationships. Many of the conclusions of this study are based on the occurrence of planktonic Foraminifera, and knowledge of their ecology is especially inadequate, being based mostly upon their distribution in sediment samples rather than in plankton. In the present paper approximately 5,000 sediment samples mainly from long, deep-sea cores, have been studied quantitatively for Foraminifera. It is belived that this work has considerably increased our understanding of the ecology and the later Cenozoic distributions, especially of the planktonic types, but also of the benthonic types.

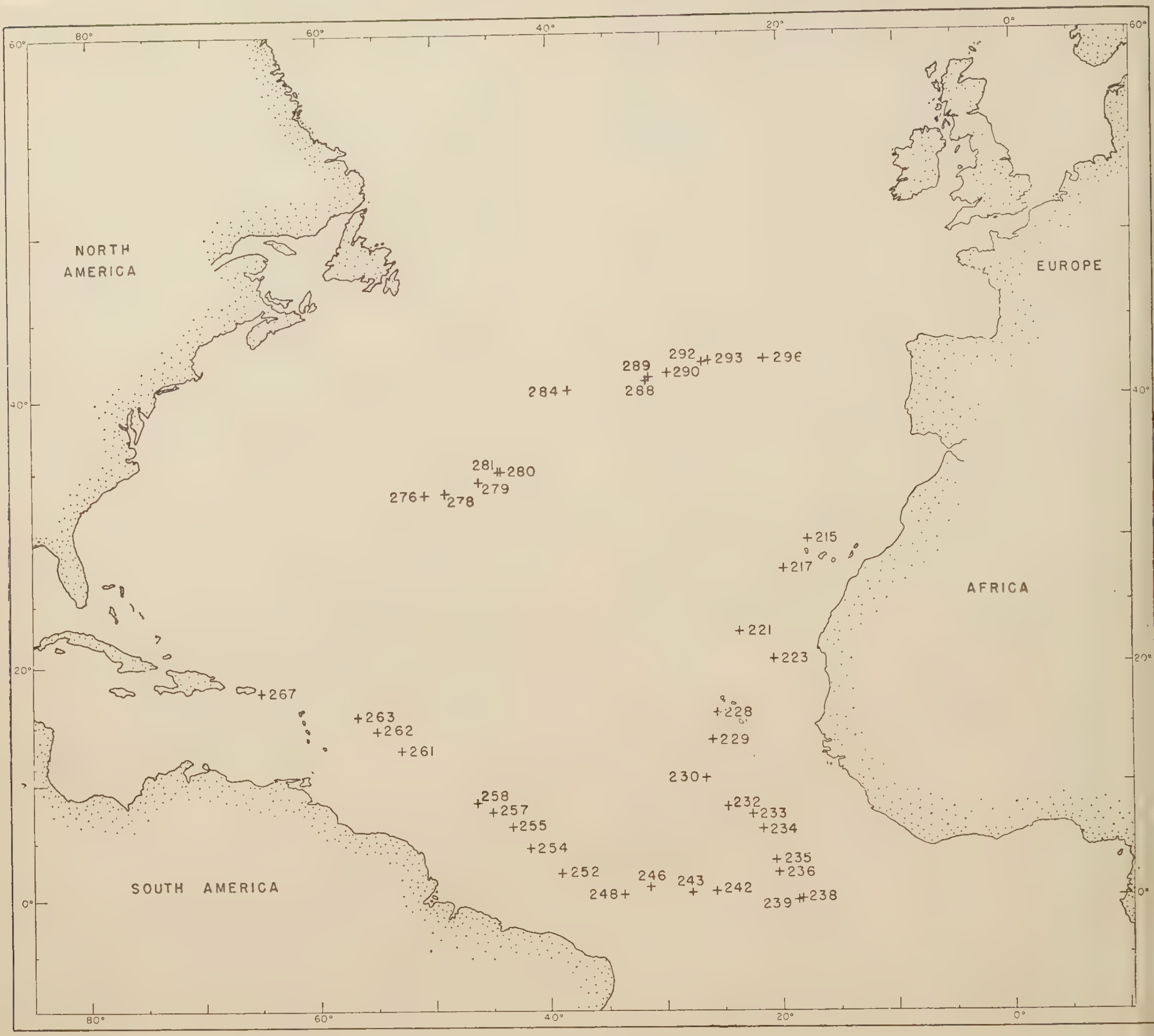
The purposes of this paper are as follows:

1. To analyze the distribution of modern, or near modern, Foraminifera contained in surface samples of deep-sea sediment, and to attempt a correlation with the known environmental conditions in this region.
2. To describe the vertical distributions of Foraminifera faunas in the cores and to attempt to interpret them from an ecological point of view.
3. To interpret the geologic ages represented by the different faunas in the cores.

The authors acknowledge with gratitude the generous cooperation of the members of Oceanografiska Institutet at Göteborg, and of the Swedish Deep Sea Expedition. Special thanks are due Professor Hans Pettersson, who provided this interesting material for study and who has assisted in numerous ways in facilitating the work. The senior author spent several days aboard the ALBATROSS as a guest of the Expedition. The present study was financed in large part by the United States Office of Naval Research (O. N. R. Project number NR 081 050). Several short cores used for study of the surface sediment were collected by the R/V ATLANTIS of the Woods Hole Oceanographic Institution and also by the USS SAN PABLO and USS REHOBETH of the U. S. Navy Hydrographic Office. The writers are grateful for this material which has been of great value in the present study.

## Locations of Stations

The cores studied for this report come from the North and Equatorial Atlantic. The southernmost station is at 00° 13′ S. Lat. and the northernmost station is at 42° 27′ N. Lat. The stations are well-distributed in both the eastern and western areas. The shoalest stations occupied were two in the mid-Atlantic Ridge area at approximately 2,000 m.; the deepest station was in the Romanche Deep at approximately 7,500 m. The majority of stations are from water deeper than 4,000 m. The samples of surface sediment collected by the Swedish Deep Sea Expedition were taken at the positions of their long core stations. Loca-


80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
292
+293
+296
289
+290
288
284+
281
+280
+279
276+
+278
+215
+217
+221
+223
+267
+263
+262
+261
+228
+229
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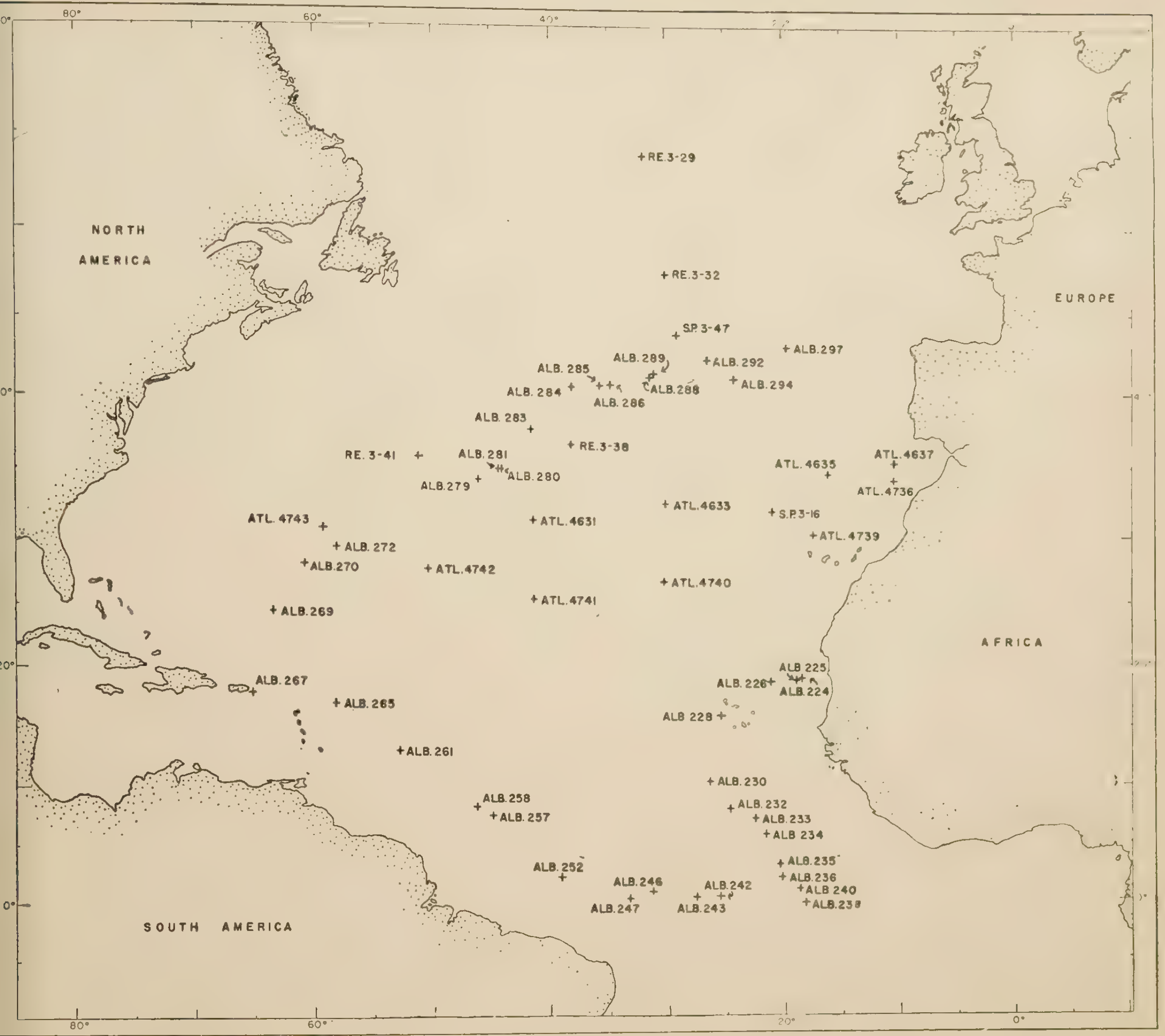
+234
+235
+236
+252
246
248+
243
+242
239
+238
80°
60°
40°
20°
0°

Fig. 1. Locations of long cores.

tions of the long cores may be seen on Figure 1, and locations of all surface sediment samples used are plotted on Figure 2. Positions and depths of water are listed on Table 1.

## Method of Study

The long, deep-sea cores were collected with the piston coring tube designed by Kullenberg (1947). The cores from the Atlantic vary from 0.5 m. to 19.3 m. in length, the average length being approximately 10 m. Twenty-two of the cores are considerably longer than 10 m. The cores were extruded aboard ship and the senior author had opportunity of examining three of these while they were being extruded ar prepared for storage. All the Atlantic cor were examined three years after collection Oceanografiska Institutet in Göteborg. It the opinion of the senior author that t Kullenberg sampler obtains a representati section of sediment which has relatively litt distortion throughout most of its length. T drag effect caused by the friction of the lin tube appears to be at a minimum for this ty of sampling. The top section of any long co however, is generally considerably disturbe this is mainly due to the semi-fluid conditi of the upper layers of sediment and because long coring tube usually must be handled


80°
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EUROPE
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RE.3-32
SP.3-47
ALB.297
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ALB.292
ALB.285
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ALB.284
ALB.288
ALB.286
ALB.283
RE.3-38
RE.3-41
ALB.281
ALB.280
ALB.279
ATL.4635
ATL.4637
ATL.4736
ATL.4633
S.P.3-16
ATL.4743
ATL.4631
ATL.4739
ALB.272
ALB.270
ATL.4742
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ALB.243
ALB.238
80°
60°
20°
0°

Fig. 2. Locations of surface sediment samples from short cores.

horizontal position on board ship. A piston rer also tends to disturb the upper sediment, pecially if the tube is not full and the piston pulled upward during extraction of the strument from the ocean floor.

Surface sediment samples were collected with e short coring tube described by Phleger 951, p. 3). This gear obtains a relatively disturbed surface sample which is emplaced a plastic tube in the form of a short core. he plastic tube containing the core is handled d stored in an upright position to prevent ixing after collection. Surface samples were llected with this type of instrument at most the coring stations occupied by the Swedish Deep Sea Expedition in the Atlantic, and this material supplements the upper sections of the cores. All the surface samples used for plotting distributions of modern Foraminifera were collected with this type of instrument.

The long cores were sliced vertically in the Göteborg laboratory. Samples for Foraminifera consisted of a horizontal slice of sediment 5 mm. in thickness taken from half sections of the cores. Approximately 3 mm. of material were trimmed from the outside of each sample to avoid faunal contamination caused by drag on the outside of the core. In general the samples were spaced 10 cm. apart throughout the length of each long core. This procedure was

## TABLE 1.

### Locations of Cores.

| Core | Latitude | Longitude | Depth in meters |
|---|---|---|---|
| 215 | 29° 55′ N | 17° 32′ W | 4320 |
| 217 | 27° 27′ N | 19° 43′ W | 4360 |
| 221 | 22° 31′ N | 23° 28′ W | 4940 |
| 223 | 20° 21′ N | 20° 37′ W | 3820 |
| 228 | 15° 53′ N | 25° 27′ W | 4280 |
| 229 | 13° 37′ N | 25° 55′ W | 4810 |
| 230 | 10° 12′ N | 26° 36′ W | 5500 |
| 232 | 07° 53′ N | 24° 43′ W | 4975 |
| 233 | 07° 13′ N | 22° 38′ W | 4125 |
| 234 | 05° 45′ N | 21° 43′ W | 3577 |
| 235 | 03° 12′ N | 20° 28′ W | 4560 |
| 236 | 02° 06′ N | 20° 07′ W | 5065 |
| 238 | 00° 07′ S | 18° 12′ W | 7315 |
| 239 | 00° 13′ S | 18° 26′ W | 7490 |
| 242 | 00° 30′ N | 25° 38′ W | 3620 |
| 243 | 00° 27′ N | 27° 45′ W | 3740 |
| 246 | 00° 48′ N | 31° 28′ W | 3210 |
| 248 | 00° 16′ N | 33° 40′ W | 4580 |
| 252 | 02° 10′ N | 39° 06′ W | 4480 |
| 254 | 04° 26′ N | 41° 47′ W | 4337 |
| 255 | 06° 17′ N | 43° 20′ W | 4490 |
| 257 | 07° 29′ N | 45° 01′ W | 4470 |
| 258 | 08° 15′ N | 46° 30′ W | 4554 |
| 261 | 12° 54′ N | 52° 55′ W | 5128 |
| 262 | 14° 32′ N | 55° 05′ W | 5480 |
| 263 | 15° 44′ N | 56° 50′ W | 5320 |
| 267 | 17° 47′ N | 65° 14′ W | 2105 |
| 276 | 33° 10′ N | 50° 53′ W | 4852 |
| 278 | 33° 16′ N | 49° 00′ W | 5520 |
| 279 | 34° 06′ N | 46° 12′ W | 4663 |
| 280 | 34° 57′ N | 44° 16′ W | 4256 |
| 281 | 34° 54′ N | 44° 20′ W | 4281 |
| 284 | 40° 32′ N | 38° 17′ W | 4257 |
| 288 | 41° 08′ N | 31° 50′ W | 2684 |
| 289 | 41° 12′ N | 31° 30′ W | 2640 |
| 290 | 41° 35′ N | 29° 37′ W | 1995 |
| 292 | 42° 16′ N | 26° 36′ W | 3216 |
| 293 | 42° 23′ N | 26° 02′ W | 3485 |
| 296 | 42° 27′ N | 21° 08′ W | 3736 |

### Locations of Surface Sediment Samples.

| Ship | Sample | Latitude | Longitude | Depth in meters |
|---|---|---|---|---|
| ALBATROSS | 224 A | 18° 50′ N | 18° 24′ W | 2810 |
| | 225 A | 18° 44′ N | 18° 44′ W | 2973 |
| | 226 A | 17° 57′ N | 21° 03′ W | 3100 |
| | 228 A | 15° 53′ N | 25° 27′ W | 4280 |
| | 230 A | 10° 12′ N | 26° 36′ W | 5500 |
| | 232 A | 07° 53′ N | 24° 43′ W | 4975 |
| | 233 A | 07° 13′ N | 22° 38′ W | 4125 |
| | 234 A | 05° 45′ N | 21° 43′ W | 3577 |
| | 235 A | 03° 12′ N | 20° 28′ W | 4560 |
| | 236 A | 02° 06′ N | 20° 07′ W | 5065 |
| | 238 A | 00° 07′ S | 18° 12′ W | 7315 |
| | 240 A | 00° 59′ N | 18° 37′ W | 7500 |
| | 242 A | 00° 30′ N | 25° 38′ W | 3620 |
| | 243 A | 00° 27′ N | 27° 45′ W | 3740 |
| | 246 A | 00° 48′ N | 31° 28′ W | 3210 |
| | 247 A | 00° 15′ N | 33° 37′ W | 4285 |
| | 252 A | 02° 10′ N | 39° 06′ W | 4480 |
| | 257 A | 07° 29′ N | 45° 01′ W | 4470 |
| | 258 A | 08° 15′ N | 46° 30′ W | 4554 |
| | 261 A | 12° 54′ N | 52° 55′ W | 5128 |
| | 265 A | 16° 51′ N | 58° 21′ W | 5832 |
| | 267 A | 17° 47′ N | 65° 14′ W | 2105 |
| | 269 A | 24° 19′ N | 63° 26′ W | 5855 |
| | 270 A | 28° 05′ N | 60° 49′ W | 5760 |
| | 272 A | 29° 21′ N | 58° 09′ W | 5450 |
| | 279 A | 34° 06′ N | 46° 12′ W | 4663 |
| | 280 A | 34° 57′ N | 44° 16′ W | 4256 |
| | 281 A | 34° 54′ N | 44° 20′ W | 4281 |
| | 283 A | 37° 37′ N | 41° 41′ W | 4940 |
| | 284 A | 40° 32′ N | 38° 17′ W | 4257 |
| | 285 A | 40° 34′ N | 35° 52′ W | 4570 |
| | 286 A | 40° 41′ N | 34° 58′ W | 4060 |
| | 288 A | 41° 08′ N | 31° 50′ W | 2684 |
| | 289 A | 41° 12′ N | 31° 30′ W | 2640 |
| | 292 A | 42° 16′ N | 26° 36′ W | 3216 |
| | 294 A | 41° 04′ N | 24° 16′ W | 3749 |
| | 297 A | 43° 04′ N | 19° 40′ W | 5980 |
| ATLANTIS | 4631 | 31° 15′ N | 41° 30 W | 1832 |
| | 4633 | 32° 28′ N | 30° 04′ W | 3245 |
| | 4635 | 34° 35′ N | 16° 11′ W | 3610 |
| | 4637 | 35° 22′ N | 10° 23′ W | 4181 |
| | 4736 | 34° 10′ N | 10° 30′ W | 4420 |
| | 4739 | 30° 06′ N | 17° 26′ W | 4363 |
| | 4740 | 26° 36′ N | 30° 09′ W | 5323 |
| | 4741 | 25° 13′ N | 41° 32′ W | 4524 |
| | 4742 | 27° 25′ N | 50° 23′ W | 5133 |
| | 4743 | 30° 37′ N | 59° 07′ W | 5531 |
| SAN PABLO | 3—16 | 31° 53′ N | 20° 54′ W | 4755 |
| | 3—47 | 43° 51′ N | 29° 07′ W | 3017 |
| REHOBETH | 3—29 | 53° 57′ N | 32° 02′ W | 2761 |
| | 3—32 | 47° 24′ N | 30° 03′ W | 3383 |
| | 3—38 | 36° 34′ N | 38° 15′ W | 3109 |
| | 3—41 | 35° 45′ N | 51° 22′ W | 4602 |

asionally modified where stratigraphic nges could be observed. In the short cores ırface sample was taken 1 cm. in thickness.

'he samples were prepared for study by shing with a water spray on a brass sieve ring an opening of 0.074 mm. which retains the adult Foraminifera and all of the enile forms except the smallest stages. aller Radiolaria, diatoms, coccoliths, and er forms of similar size are not retained.

n study of the dried samples only the tion retained on a brass sieve having an rage opening of 0.149 mm. was examined. entially all the larger forms, presumably ılts, were retained on this sieve.

Each sample was examined in detail, begin- g with the top sample in each core. A cies count was made of the top sample l of each succeeding sample lower in the e where any faunal differences from the vious population could be detected. Where re were no faunal differences through eral samples, at least each fifth sample was nted. Samples containing more than about planktonic specimens were quartered, using device described by Parker (1948, p. 218). less than about 300 planktonic specimens e counted in each sample where sufficient cimens were present. In most samples all benthonic specimens were counted due to ir relative rarity. Occurrences of species listed as percentages of total populations, l the faunal data for each sample are divided o a planktonic and a benthonic group. e percentage occurrences are listed separa- for both groups so that each constitutes %; this is the only valid quantitative ıtment of Foraminifera from an ecological nt of view. Total populations were estima- for each sample exclusive of the small ns not retained on the 0.149 mm. sieve.

everal additional observations were made each sample. An estimate of the percentage broken shells of Foraminifera was made, presence of Radiolaria and other skeletal remains and the occurence of sand, volcanic materials and any unusual minerals was recorded.

One of the problems in study of submarine sediment cores is the relatively small amount of sediment available. In study of land geology, exposures in some places are sufficient to obtain a three-dimensional view of materials, but this is impossible at the present time in submarine geology. The piston coring tube obtains a cross-section which is only about 2 inches in diameter, and the small coring tube sample has a diameter of 1—3/8 inches. This material is assumed to be representative of a much larger area, although this assumption is not necessarily true in any absolute sense. This qualification should be kept in mind in evaluating the quantitative data on distribution of Foraminifera in the samples studied.

Another problem in ecological study of Foraminifera from sediment samples is that of obtaining samples of equivalent sizes, as well as methods of presenting the data. Said (1950) in his study of samples from the Red Sea has adopted the system proposed by Schott (1935) in his extensive study of deep-sea cores from the equatorial Atlantic, although Schott did not use it in his plots of distributions. According to this method, occurrences of species are given as numbers of specimens per gram (dry weight) of sediment. This is called the »foraminiferal number».

The principal advantage of this method is that the results may be more comparable to the present occurrences in essentially dry rocks deposited during the geologic past. The principal difficulty of using the »foraminiferal number» is that there is no common arithmetic base for comparison of the numbers. This makes it almost impossible to compare the species composition of different faunas without tedious manipulation of the data. Moreover, the use of a standard size of sample based upon dry weight seems to be an artifical measure for ecological purposes. This criticism is more applicable to ecologic studies of the modern and near-modern faunas than to studies of vertical distribution of faunas in cores, which was the main emphasis in Schott's 1935 study.

The procedure adopted by the writers is to use volume and area as a measure of size of sample. In any ecological study it appears that area is an important measure which must be considered, and this is especially true when dealing with benthonic populations. The use of a coring tube for sampling sediment will obtain a constant area of sediment if reasonable care is exercised in the operation. It is suggested that the living space of a population is also three-dimensional. At and near the surface of the sediment the sea water constitutes an integral part of the living space. It is suggested that volume and area may be a more reliable measure for ecological study of Foraminifera than the dry-weight measure. To use this method, however, the sediment should have essentially its original water content, which is largely a problem in proper handling and storage of samples. 110 of the present samples selected at random were weighed before washing; these gave an average weight of approximately 3 grams. It is suggested that this may be taken as an average weight of the samples studied, all of which were of uniform volume in their original condition. The occurrence data presented can therefore be converted into »foraminiferal number» if this is desired.

## The Foraminifera Species

### *Planktonic Species*

The following discussion is concerned chiefly with the identification of the planktonic species and their reported distribution in the literature. The distributions listed cover only occurrences reported in the North Atlantic and occasionally in related areas. The distribution in the Swedish Deep Sea Expedition cores and surface samples is discussed in detail elsewhere. The references used are included in the synonymies under each species. In many cases it was possible to check these by an examination of the types. This was true for almost all American publications and a few others whose authors had deposited types at the U. S. National Museum in Washington. In most other cases, figures were given which were studied carefully. It is believed that the synonymies truly represent the species as we have identified them. This includes the fossil forms, also. In no case, except for an occasional reference such as that of Schott (1935) where no figures were given, are references included in the synonymy because a species is identified by the same specific name.

A few species occurring near the bottom of several cores are believed to be at least pre-Pliocene in age. These include: *Globigerina altispira* Cushman and Jarvis, *G. venezuelana* Hedberg, *Sphaeroidinella rutschi* Cushman and Renz (which may also include *S. seminulina* Schwager) and probably *Globorotalia* sp. 2 and *G. multicamerata* Cushman and Jarvis. A study of the literature shows that these species, exclusive of *Globorotalia* sp. 2 and possibly *G. multicamerata*, have an overall common occurence from the Upper Oligocene to the Middle Miocene in the general West Indian — Caribbean region. Further discussion of these fossil species and their significance in the cores will be given later in the section on the interpretation of core faunas as well as in the species discussions.

### **Sphaeroidina bulloides** d'Orbigny

(Plate 1, figure 5)

*Sphaeroidina bulloides* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 267, no. 1; Modèles, no. 65.

This species is reported from Brazil to Cape Cod with its highest frequency between Cape Cod and Cape Hatteras. Parker (1948) reports

n the continental shelf of the northeastern
ited States south of Cape Cod with frequen-
s of less than 1 % in most cases except
samples shallower than 250 m. where it
y form as much as 15 % of the planktonic
na.

lthough the species is found in small num-
s in the cores it does not occur in the surface
nples with significant frequencies. It is
estionable whether or not it is a planktonic
ecies and therefore it is listed in that group
Tables 2—37 in brackets. In all cases it
ms a very small part of the total plank-
ic fauna. The findings of Parker given
ove point to the strong probability that
s is a benthonic form, which is the opinion
most authors. It has not, as far as can be
ertained, been observed in plankton tows.

### **obigerina altispira** Cushman and Jarvis

(Plate 1, figures 1, 2, 6)

*obigerina altispira* Cushman and Jarvis, 1936,
Contr. Cushman Lab. Foram. Res., vol.
12, pt. 1, p. 5, pl. 1, figs. 13, 14. — Bermudez,
1949, Spec. Publ. 25, Cushman Lab. Foram.
Res., p. 277, pl. 21, fig. 43.

This species appears to be related to *G.*
*eri* Rhumbler but has a much higher spire.
is reported from the Bowden Marl of
maica by Cushman and Jarvis and from
e Miocene and Upper Oligocene of the
ominican Republic by Bermudez, the chief
currence being in the Middle Miocene Gurabo
rmation which is correlated with the Bowden
arl. The specimen figured by Coryell and
vero (1940, p. 339, pl. 42, fig. 31) from the
ocene of Port-au-Prince, Haiti appears to
long here also. They correlate this formation
ntatively with the Bowden marl but believe
at it represents a deeper water deposit. The
ecimen figured by Dorsey (1948, p. 313, pl.
, fig. 3) from the Calvert Formation of
aryland probably does not represent this
ecies. The species has also been recorded by Colom (1946, p. 56, pl. 3, figs. 69, 73, 74) from the Burdigalian of the Balearic Islands, Spain, but these figures have not been seen. The specimens figured by Cushman and Todd (1945, p. 66, pl. 11, figs. 11, 12) from the Miocene of Buff Bay, Jamaica, should be referred to *G. venezuelana* Hedberg.

The range established for this species at the present time is from the Upper Oligocene to the Upper Miocene. It appears to occur most abundantly in the Middle Miocene as exemplified by the Bowden marl of Jamaica, the Port-au-Prince beds of Haiti and the Gurabo Formation of the Dominican Republic.

### **Globigerina bulloides** d'Orbigny

(Plate 1, figures 3, 4, 7, 8)

*Globigerina bulloides* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 277, no. 1; Modèles no. 76; and young, no. 17. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 593, pl. 77; pl. 79, figs. 1—7 (Fig. 5 may represent *Globigerinoides rubra*). — Cushman, 1924, Bull. 104, U. S. Nat. Mus., p. 7, pl. 2, figs. 1—4 (questioned in explanation of plate but figures appear to represent this species). — Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 3, figs. 15, 16; 1942, ibid., vol. 53, p. 1087. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, p. 46, pl. 8, figs. 2 a—c. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, figs. 1, 2. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 65, pl. 2, figs. 3 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 34, pl. 19, figs. 6, 7.

This species is listed from the Arctic by authors but there is no specific data on frequencies. It is recorded from Lat. 60 ° N with a frequence of 18 %; southwest of the British Isles 28 %; between this point and Newfoundland abundant; on the continental shelf and slope of northeastern United States south of Cape Cod 50 %, although the general average is lower than this; in the Gulf of Mexico 10—20 %; off the African coast from Lat. 0—20 ° N it varies from ± 1 % to the south to 10+ % to the north.

### **Globigerina digitata** H. B. Brady

(Plate 1, figures 9, 10)

*Globigerina digitata* H. B. Brady, 1879, Journ. Micr. Sci., vol. 19, p. 72; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 599, pl. 80, figs. 6—10; pl. 82, figs. 6, 7.

This species is reported to be rare in the North and South Atlantic. It is not found with significant frequencies in surface samples.

### **Globigerina eggeri** Rhumbler

(Plate 1, figures 11, 12)

*Globigerina dubia* H. B. Brady (not Egger, 1857), 1879, Quart. Journ. Micr. Sci., vol. 19, n. ser., p. 71; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 595, pl. 79, figs. 17 a—c; — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 8, pl. 2, figs. 5—8. — Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, p. 1404, pl. 1, figs. 14, 15. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 67, pl. 3, figs. 10 a, b.

*Globigerina eggeri* Rhumbler, 1900, Nordische Plankton, pt. 14, Foraminiferen, p. 19, text. figs. 20 a—c. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, figs. 5, 6. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 34, pl. 19, figs. 8, 9.

*Globigerina conglomerata* Cushman (not Schwager, 1866), 1941, Amer. Journ. Sci., vol. 239, pl. 1, fig. 3. — Phleger, 1942, Geol. Soc. America, vol. 53, p. 1087.

The species as defined here has little variation except for the specimens from the more northern cores. These specimens are smaller than those figured but otherwise maintain the characteristics of the species. Ovey points out that his species »*G. dubia*» varies from forms referable to *G. subcretacea* Lomnicki to *G. eggeri* Rhumbler. There are no specimens referable to the former species in our North Atlantic material. Pacific specimens kindly sent by Miss Ruth Todd have been used for study. They show a low-spired form with an average of 6 chambers in the last-formed whorl. *G. eggeri* usually has 5 chambers. The figures given by Ovey show a form identical with our species.

This species is recorded as far north as Lat. 60° N where it is rare. It has a frequency of 6 % southwest of the British Isles; highest frequencies of about 50 % occur along the continental shelf of northeastern United States south of Cape Cod; eastward on the slope the frequencies drop to between 10 % and 20 %. It is of interest to note that the species was not recorded by Cushman and Henbest in the cores taken across the Atlantic between Newfoundland and the British Isles. In the Gulf of Mexico the frequencies vary between 5 % and 20 %. Similar frequencies are found off the African coast between Latitudes 0° and 20° N. In general the species is reported in significant numbers between Latitudes 0° and 50° N with the highest frequencies between 20° and 40° N.

### **Globigerina hexagona** Natland

(Plate 1, figures 13, 14)

*Globigerina hexagona* Natland, 1938, Bull. Scripps Instit. Ocean., Techn. Ser., vol. 4, no 5, p. 149, pl. 7, figs. 1 a—c.

The specimens were compared to the holotype and found to be identical. This species as not previously been reported from the tlantic. It is not found in significant numbers surface samples but occurs in cores between at. 0° and 20° N with one or two rare ccurrences farther north. The species was escribed from 884 m. off the coast of southern alifornia and Natland states that it was found nly in his deeper samples in the area.

### **Globigerina inflata** d'Orbigny

(Plate 1, figure 15, 16)

*lobigerina inflata* d'Orbigny, 1839, in Barker-Webb, and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, »Foraminifères», p. 134, pl. 2, figs. 7—9. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 601, pl. 79, figs. 8—10. — Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped., Forsch. Vermess. »Meteor», 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 12, pl. 3, figs. 1—3. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 3, figs. 18, 19; 1942, ibid., vol. 53, p. 1087. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, pl. 8, fig. 4. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 6, figs. 12, 13. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 66, pl. 2, figs. 5 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 34, pl. 19, figs. 10, 11.

*loborotalia punctulata* Cushman and Bermudez (not d'Orbigny, 1826), 1949, Contr. Cushman Lab. Foram. Res., vol. 25, pt. 2, p. 42, pl. 8, figs. 7—9.

Brady gives an over-all distribution of this pecies in the Atlantic from 82° 27′ N to 3° 55′ S. It occurs with a frequency of 5 % t Lat. 60° N. This increases to 54 % southwest of the British Isles. It is listed as common o abundant between this point and Newfoundland. On the western Atlantic continental shelf and slope off the United States south of Cape Cod it ranges from 10—20 % on the shelf to 50 % on the slope. In the Gulf of Mexico it is very rare and is found east of Cuba with a frequency of 0.6 %. Off the coast of Africa between Latitudes 0° and 20° N it ranges from ±1 % in the south to 20+ % in the north. This gives a range of high frequency from 50° N to about 20° N excluding the Gulf of Mexico. The highest known frequencies reported are from north of Latitude 35° N.

### **Globigerina pachyderma** (Ehrenberg)

(Plate 1, figures 17, 18, 19)

*Aristerospira pachyderma* Ehrenberg, 1861, Monats. k. preuss. Ak., Wiss. Berlin, p. 303; 1872 (1873) Abhandl. Ak. k. Wiss. Berlin, pl. 1, fig. 4.

*Globigerina pachyderma* (Ehrenberg), Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 2, figs. 1, 2; 1942, ibid., vol. 53, p. 1087. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, pl. 8, fig. 1. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 65, pl. 2, figs. 2 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 73; Phleger and Parker, ibid., pt. 2, p. 35, pl. 19, figs. 12, 13.

This species as defined here may include some forms listed by authors as *G. dutertrei* d'Orbigny. That species has been interpreted by Brady (1884, p. 601) as a typical Antarctic species and this interpretation has been followed by a number of authors. As the species was originally described by d'Orbigny from the vicinity of Cuba it seems unlikely the Antarctic and Arctic species is referable to it.

*G. pachyderma* is not reported south of Lat. 20° N in the North Atlantic. It occurs at Lat. 60° N with a frequency of 72 % decreasing to 0.8 % southwest of the British Isles. Westward from this point it is listed as abundant to common in some samples, less frequently in others. On the continental slope off the United States it ranges from 0—5 %. It is reported east of Cuba with a frequency of 0.08 %.

### **Globigerina quinqueloba** Natland

(Plate 1, figures 20, 21)

*Globigerina quinqueloba* Natland, 1938, Bull. Scripps Instit. Ocean., Techn. Ser., vol. 4, no. 5, p. 149, pl. 6, figs. 7 a—c.

The Atlantic specimens are identical with the holotype. The species has not been reported in the Atlantic. Natland reports it in the Pacific ranging from off Panama to off Long Beach, California.

### **Globigerina venezuelana** Hedberg

(Plate 1, figures 24, 25)

*Globigerina venezuelana* Hedberg, 1937, Journ. Pal., vol. 11, no. 8, p. 681, pl. 92, fig. 7. — Cushman and Stainforth, 1945, Spec. Publ. 14, Cushman Lab. Foram. Res., p. 67, pl. 12, fig. 13. — Stainforth, 1948, Journ. Pal., vol. 22, no. 1, p. 119, pl. 25, figs. 26—28. — Bermudez, 1949, Spec. Publ. 25, Cushman Lab. Foram. Res., p. 280, pl. 21, figs. 39, 40.

*Globigerina* sp. Cushman and Jarvis, 1930, Journ. Pal. vol. 4, no. 4, p. 366, pl. 34, figs. 5 a, b.

*Globigerina altispira* Cushman and Todd (not Cushman and Jarvis, 1936), 1945, Spec. Publ. 15, Cushman Lab. Foram. Res., p. 66, pl. 11, fig. 11.

Specimens in a few cores are identical with the holotype. It is possible that this species should be referred to *G. conglomerata* Schwager. Only one view of that species is figured and Schwager describes it as having a diameter of 0.6 mm. whereas Pacific specimens attain
a diameter of almost 1.00 mm. Since there
therefore, considerable doubt of this identi
cation it seems safer to use Hedberg's nam
Brady (1884, p. 596) notes that specime
sent to him by Schwager resemble »*G. dubi*
Egger and are not well illustrated by Schw
ger's figure.

The references given in the above synony
have all been checked with types deposited
the U. S. National Museum. The species
described from the Carapita Formation
Venezuela, of Oligocene age. It is report
from the Upper Oligocene of the Dominic
Republic; from the Apero marl in the Oligoce
of Trinidad; from Ecuador — ranging fro
the Lower Oligocene to the Middle Mioce
with the chief occurrence in the upper Midd
and Upper Oligocene; and from the Buff B
Formation of the Miocene in Jamaica. Palm
(1941, p. 286) reports a form questionab
referable to this species from the Cojimar F
mation, Upper Oligocene of Cuba. In the W
Indian and South American regions the sp
cies appears to be most common in the upp
Middle and Upper Oligocene, although
range extends above into the Miocene a
below into the Lower Oligocene.

### **Globigerina** sp. 1

(Plate 1, figures 22, 23)

This is a very small form, having a th
smooth wall. It is of rare occurance.

### **Globigerina** sp. 2

(Plate 1, figures 26, 27)

This form bears some resemblance to
*hexagona* Natland but is smaller, usually h
6 chambers in the last-formed whorl wh
increases less rapidly in size as added, and h
a finer hexagonal pattern in the wall.
occurs in several cores but not in the surf
samples.

**obigerinoides conglobata** (H. B. Brady)

(Plate 2, figures 1, 2, 3)

*obigerina conglobata* H. B. Brady, 1879, Quart. Journ. Micr. Sci., vol. 19, p. 72; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 603, pl. 80, figs. 1—5; pl. 82, fig. 5. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 18, pl. 3, figs. 8—13.

*obigerinoides conglobata* (H. B. Brady), Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 1, fig. 8; 1942, ibid., vol. 53, p. 1088. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, p. 46, pl. 8, fig. 10. — Cushman, 1941, Amer. Journ. Sci., vol. 239, pl. 2, fig. 2. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, figs. 8, 9. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 68, pl. 3, figs. 8 a, b. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, ibid., pt. 2, p. 35, pl. 19, fig. 15.

This species is reported from the western tlantic on the continental shelf and slope off e United States south of Cape Cod with equencies from 0—5 %; in the Gulf of Mexico ith a frequency of 5 %; east of Cuba at 2 %; tween Lat. 0° and 20° N off the African ast, ±1 % at the south increasing to greater an 5 % to the north. Brady reports its currence from Lat. 40° N to 35° S. This rthern limit is not expanded by later authors.

**Globigerinoides rubra** (d'Orbigny)

(Plate 2, figures 4, 7)

*lobigerina rubra* d'Orbigny, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 82, pl. 4, figs. 12—14. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 602, pl. 79, figs. 11—16. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 15, pl. 3, figs. 4—7.

*Globigerinoides rubra* (d'Orbigny), Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B., p. 59. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 1, fig. 12; ibid., 1942, vol. 53, p. 1087. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, p. 46, pl. 8, fig. 9. — Cushman, 1941, Amer. Journ. Sci., vol. 239, pl. 2, fig. 3. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, fig. 4. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 68, pl. 3, figs. 12 a, b. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 35, pl. 19, fig. 16.

It is possible that some of the forms reported as *Globigerina helicina* d'Orbigny should be included here. This species varies a good deal in shape, number of chambers, etc., but is uniform as regards the character of the wall.

It is reported southwest of the British Isles with a frequency of 0.1 %; between this point and Newfoundland it is absent or rare in a few samples; on the continental shelf of the northeastern United States south of Cape Cod it occurs with average frequencies of 0—3 % increasing to 5—10 % on the slope, although occasionally it may form as much as 50 % of the planktonic fauna; in the Gulf of Mexico it has frequencies of 30—70 %; east of Cuba 17 %; from Lat. 0°—20° N off the coast of Africa it forms 10 % of the fauna to the north increasing to 19 % at 0°; to the westward it decreases to ± 1 % toward the coast of South America. The highest average frequencies occur in the Gulf of Mexico. It is reported by Brady from 49° N to 36° S in the Atlantic with the greatest abundance in the tropics.

### Globigerinoides sacculifera (H. B. Brady)

(Plate 2, figures 5, 6)

*Globigerina sacculifera* H. B. Brady, 1877, Geol. Mag., vol. 4, p. 535; 1879, Quart. Journ. Micr. Sci., vol. 19, p. 73; 1884 Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 604, pl. 80, figs. 11—17; pl. 82, fig. 4. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 21, pl. 4, figs. 1—6.

*Globigerinoides sacculifera* (H. B. Brady), Schott 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 1, figs. 16, 17; ibid., 1942, vol. 53, p. 1088. — Cushman, 1941, Amer. Journ. Sci., vol. 239, pl. 3, fig. 1. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, fig. 7. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 68, pl. 3, fig. 5. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 35, pl. 19, figs. 17, 18.

This species occurs on the western Atlantic continental shelf and slope of the northeastern United States south of Cape Cod with frequencies of 0—5 %; occasionally 10 %; in the Gulf of Mexico 5—10 %; east of Cuba 24 %; off the coast of Africa from 0°—20° N with varying frequencies of 24 % to the north decreasing to the south to 10 % and again increasing to 60 % at about Lat. 10° N; at 0° there are frequencies of 20—40 %, to the westward the frequencies decrease to 20 % and then increase to 50 % near the coast of South America. Brady gives the distribution in the Atlantic from 40° N to 35° S.

### Globigerinita glutinata (Egger)

(Plate 2, figures 12, 13, 14, 15)

*Globigerina glutinata* Egger, 1893, Abhandl. k. bay. Akad. Wiss München, Cl II, vol. 18, p. 371, pl. 13, figs. 19—21. — Rhumbler,
1911, Ergeb. Plankton-Exped. Humbol
Stift., vol. 3, p. 148, pl. 29, figs. 14—26;
33, fig. 20; pl. 34, fig. 1.

In identifying this species Rhumbler's int
pretation has been followed. Egger's figu
are poor and he makes no mention, in t
description, of the supplementary chambe
It is possible, however, that Rhumbler h
access to Egger's material on which to ba
his identification. The species has been plac
in the genus *Globigerinita* although occasio
specimens have a second globigerine apertu
The occurrence of the secondary chambers
a variable feature; in some assemblages th
are found in a large percentage of the specime
whereas in others they may be quite subor
nate. The species may be easily defined, howe
from the general characters of the test. It
much smaller than *Globigerinoides rubra*, a
has a thinner, more finely spinose w
It differs from the genotype: *Globigerin
naparimaensis* Bronnimann, in that the w
of the supplementary chambers is mu
smoother and more finely perforate than t
rest of the test.

There are no reports of this species
bottom sediments except Egger's at ab
10° N Lat. off the coast of Africa in 677
where he reports it as rare. Specimens ha
been observed in material from the nor
western Gulf of Mexico.

### Globigerinella aequilateralis (H. B. Bra

(Plate 2, figures 9, 10, 11)

*Globigerina aequilateralis* H. B. Brady, 18
Quart. Journ. Micr. Sci., vol. 19, p.
1884, Rep't. Voy. CHALLENGER, Zo
vol. 9, p. 605, pl. 80, figs. 18—21.
Cushman, 1924, Bull. 104, U. S. Nat. M
pt. 5, p. 25, pl. 4, figs. 7, 8.

*Globigerinella aequilateralis* (H. B. Brad
Schott, 1935, Wiss. Ergeb. deutsch. Atl
tisch. Exped. Forsch. Vermess. »Mete
1925—1927, vol. 3, pt. 3, Sect. B, p. 59.

hleger, 1939, Bull. Geol. Soc. America, vol. 
), p. 1405, pl. 1, figs. 11, 13; 1942, ibid., vol. 
3, p. 1096. — Cushman and Henbest, 1940, 
. S. Geol. Surv. Prof. Paper 196-A, pt. 2, 
l. 8, fig. 11. — Cushman, 1941, Amer. 
ourn. Sci., vol. 239, pl. 2, fig. 1. — Parker, 
948, Bull. Mus. Comp. Zool., vol. 100, no. 
, p. 238. — Ovey, in Wiseman and Ovey, 
950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 
8, pl. 3, figs. 9 a, b. — Phleger, 1951, Mem. 
6, Geol. Soc. America, pt. 1, p. 68; Phleger 
nd Parker, ibid., pt. 2, p. 35, pl. 19, fig. 14.

'his species is reported with a frequency 
0.3 % southwest of the British Isles; 
asionally rare between this point and 
wfoundland; on the continental shelf and 
e of the northeastern United States south 
Cape Cod, 0—1 %; in the Gulf of Mexico 
; east of Cuba 13 %; off the coast of 
ica from Lat. 0°—20° N mostly ± 1 % 
ough Ovey reports 7 % near the equator. 
dy gives a distribution in the Atlantic 
n 50° N to 35° S.

### **Orbulina universa** d'Orbigny

(Plate 2, figure 8)

*ulina universa* d'Orbigny, 1839, in de la 
agra, Hist. Phys. Pol. Nat. Cuba, »Forami- 
ifères», p. 3, pl. 1, fig. 1. — Brady, 1884, 
ep't. Voy. CHALLENGER, Zool., vol. 9, 
. 608, pl. 78; pl. 81, figs. 8—26; pl. 82, 
igs. 1—3. — Cushman, 1924, Bull. 104, 
. S. Nat. Mus., pt. 5, p. 28, pl. 5, figs. 
—9; 1941, Amer. Journ. Sci., vol. 239, 
l. 4, fig. 2. — Schott, 1935, Wiss. Ergeb. 
eutsch. Atlantisch. Exped. Forsch. Ver- 
ıess. »Meteor» 1925—1927, vol. 3, pt. 3, 
ect. B, p. 59. — Phleger, 1939, Bull. Geol. 
oc. America, vol. 50, p. 1401; 1942, ibid., 
ol. 53, p. 1088. — Cushman and Henbest, 
940, U. S. Geol. Surv. Prof. Paper 196-A, 
t. 2, pl. 8, fig. 8. — Ovey, in Wiseman 
nd Ovey, 1950, Proc. Geol. Assoc., vol. 
1, pt. 1, p. 67, pl. 3, fig. 6. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 35.

This species is reported southwest of the British Isles with a frequency of 2 %; westward to Newfoundland it occurs with varying abundance but mostly rarely; on the northeastern United States continental shelf and slope 0—1 %; in the Gulf of Mexico 5 %; east of Cuba 23 %; off the coast of Africa from Lat. 0° to 20° N, mostly ± 1 % although one report near the equator gives a frequency of 7 %. Brady gives a range of the species from Nova Zembla to 50° S Latitude.

### **Pulleniatina obliquiloculata**

(Parker and Jones)

(Plate 2, figures 16, 17, 18)

*Pullenia obliquiloculata* Parker and Jones, 1865, Phil. Trans., vol. 155, p. 368, pl. 19, figs. 4 a, b. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 618, pl. 84, figs. 16—20. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 43, pl. 8, fig. 10.

*Pulleniatina obliquiloculata* (Parker and Jones), Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Cushman, 1941, Amer. Journ. Sci., vol. 239, pl. 4, fig. 3. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, fig. 13. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 69, pl. 3, fig. 7. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., p. 35, pl. 19, figs. 19, 20.

This species is reported on the northeastern continental shelf of the United States south of Cape Cod with frequencies of 0—5 % decreasing eastward on the slope to less than 1 % (Phleger, 1942); in the Gulf of Mexico 10—20 %; east of Cuba 0.2 %; off the coast of Africa the frequency at 20° N is ± 1 % increasing to ± 10 % at the equator and also to the westward toward the coast of South America. The highest frequencies are found in the Gulf of Mexico with a somewhat lower occurrence near the equator extending northward along the coast of South America.

### **Sphaeroidinella dehiscens** (Parker and Jones)

(Plate 2, figure 19)

*Sphaeroidina dehiscens* Parker and Jones, 1865, Phil. Trans., vol. 155, p. 369, pl. 19, figs. 5 a-c. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 621, pl. 84, figs. 8—11. — Cushman, 1924, Bull. 104, U. S. Nat. Mus., pt. 5, p. 38, pl. 7, figs. 7, 8; pl. 8, figs. 1, 2.

*Sphaeroidinella dehiscens* (Parker and Jones), Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 59. — Cushman, 1941, Amer. Journ. Sci., vol. 239, p. 136. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, p. 239. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 69, pl. 3, fig. 4. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., p. 35.

This species occurs rarely on the continental shelf south of Cape Cod; in the Gulf of Mexico; east of Cuba with a frequency of 0.7 %; off Africa from Lat. 0° to 20° N with a frequency of ± 1 %. Brady reports its occurrence in the tropical and subtropical areas of the Atlantic and rare occurrence in the vicinity of the British Isles. Cushman (1924) places its northern limit at Lat. 40° N.

### **Sphaeroidinella rutschi** Cushman and Renz

(Plate 2, figures 20, 21)

*Sphaeroidinella rutschi* Cushman and Renz, 1941, Contr. Cushman Lab. Foram. Res., vol. 17, pt. 1, p. 25, pl. 4, fig. 5. —
Bermudez, 1949, Spec. Publ. 25, Cushma
Lab. Foram. Res., p. 283, pl. 21, fig. 60.

The smaller specimens of our species a
identical with the holotype, but the ran
of variation is somewhat different from th
shown by the paratypes in that our specime
show a more lobulate form. The identificatio
however, appears to be a close one. The
is some resemblance between this species a
*S. seminulina* (Schwager) but the latter h
only three chambers in the adult form wh
*S. rutschi* frequently has 4 according to t
description. In our assemblages specime
with 5 chambers are occasionally seen.

There seems to be a possibility, howeve
that *S. rutschi* and *S. seminulina* may
closely related and may even be synonymou
This point cannot be ascertained without lar
suites of fossil material which we do not ha
available. The two species appear to have
somewhat similar range in the West Indi
region. *S. rutschi* is reported by Cushm
and Renz from Lower through Middle Mioce
in Venezuela in the lower and upper Ag
Salado Formation. Bermudez reports it fro
the Upper Oligocene of the Dominican Rep
blic, giving an over-all range of lowermo
Miocene through Middle Miocene. The ran
of *S. seminulina* as reported by various autho
from the West Indian region is from the Upp
Oligocene through the Upper Miocene.

### **Candeina nitida** d'Orbigny

(Plate 2, figures 22, 23)

*Candeina nitida* d'Orbigny, 1839, in de
Sagra, Hist. Phys. Pol. Nat. Cuba, »Fo
minifères», p. 108, pl. 2, figs. 27, 28. — H.
Brady, 1884, Rep't. Voy. CHALLENGE
Zool., vol. 9, p. 622, pl. 82, figs. 13—20.
Cushman, 1924, Bull. 104, U. S. Nat. Mu
pt. 5, p. 35, pl. 5, fig. 1. — Schott, 19
Wiss. Ergeb. deutsch. Atlantisch. Exp
Forsch. Vermess. »Meteor» 1925—1927, v
3, pt. 3, Sect. B, p. 59.

rady reports this species in the North ntic as far north as 55° 11′ (one station ). Cushman (1924) says that it is found fly in the Caribbean and is not to be found h of Cape Hatteras, at approximately . 35° N. This seems more in accordance the other published occurrences. Schott rds it as absent or rare in the area off the can coast from Lat. 0° to 20° N.

### **Globorotalia hirsuta** (d'Orbigny)

(Plate 4, figures 1, 2, 3, 4, 5, 6, 7)

*lina hirsuta* d'Orbigny, 1839, in Barker-ebb and Berthelot, Hist. Nat. Îles Cana-es, vol. 2, pt. 2, »Foraminifères», p. 131, l. 1, figs. 37—39.

*vinulina canariensis* H. B. Brady (not 'Orbigny, 1839), 1884, Rep't. Voy. CHALL-NGER, Zool., vol. 9, p. 692, pl. 103, figs. —10.

*orotalia hirsuta* (d'Orbigny), Cushman, 931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 99, l. 17, figs. 6 a—c. — Phleger, 1939, Bull. eol. Soc. America, vol. 50, pl. 1, figs. 3, 4; Cushman and Henbest, 1940, U. S. Geol. urv. Prof. Paper 196—A, pt. 2, pl. 8, fig. . — Parker, 1948, Bull. Mus. Comp. Zool., ol. 100, no. 2, pl. 7, figs. 11, 14. — Ovey, Wiseman and Ovey, 1950, Proc. Geol. ssoc., vol. 61, p. 67, pl. 2, figs. 6 a—c.

his species has been confused by authors the species referred by us to *G. punctulata* rbigny) which is plano-convex in all cases. is the case with the *G. hirsuta* of Cushman Bermudez (1949, p. 36, pl. 7, figs. 1—3) ch represents a variant of *G. punctulata* an acute periphery. The form referred Ovey (Wiseman and Ovey, 1950, p. 60, pl. gs 4 a, b) to *G. canariensis* (d'Orbigny) is ably a variant form of *G. hirsuta*. He re-s it in small quantities from the same lities at which he found that species. In many cases we have found associated with typical *G. hirsuta* a small compact form with a thickened periphery (pl. 4, figs. 6, 7). It usually forms a small percentage of the total occurrence of *G. hirsuta* and has been included with that species in the species counts. This form resembles the holotype of *G. crassula* Cushman and R. E. Stewart which is such a poor specimen that there is some difficulty in distinguishing its characteristics.

It is probable that the two species groups, *G. hirsuta* and *G. punctulata*, may be closely related. They are differentiated by the shape of the test, but the number and shape of the chambers is similar. Both species groups show great variation in the character of the periphery from acute to subacute or even almost rounded in extreme cases. It is inadvisable to further subdivide these forms into subspecies owing to the confusion that already exists. It seems better to refer specimens to one of the two groups, based on the shape of test which can be readily distinguished, and to point out the variant forms which may occur in any given case.

*G. hirsuta* is reported with frequencies of less than 1 % at Lat. 60° N and southwest of the British Isles. Between this point and Newfoundland it is common to abundant according to Cushman and Henbest; on the northeastern continental shelf and slope of the United States south of Cape Cod it has a frequency of less than 1 %; in the Gulf of Mexico it is rare; east of Cuba 0.1 %; It was originally described from the Canary Islands and is probably the form referred by Schott to *G. canariensis* (1935, p. 105) which he reports as occurring rarely off the coast of Africa from Lat. 0° to 20° N.

### **Globorotalia menardii** (d'Orbigny)

(Plate 3, figures 1, 2, 4, 5)

*Rotalia menardii* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 273, no. 26; Modèles no. 10.

*Pulvinulina menardii* (d'Orbigny), H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 690, pl. 103, figs. 1, 2.

*Globorotalia menardii* (d'Orbigny), Cushman, 1931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 91, pl. 17, figs. 1 a—c; 1941, Amer. Journ. Sci., vol. 239, pl. 3, fig. 2. — Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 60. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 1, figs. 1, 2; 1942, ibid., vol. 53, p. 1093. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, p. 46, pl. 8, fig. 3. — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, fig. 10. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc. vol. 61, pt. 1, p. 69, pl. 3, figs. 1 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 36, pl. 20, figs. 1, 2.

This species is easily separable from the typical form of *G. tumida* (H. B. Brady) in surface samples and the upper part of most cores as it is a much less tumid form with a more rounded outline. Farther down in the cores specimens occur which combine characteristics of the two species. These are listed in the tables as »*menardii-tumida* group». Various forms included in this group are figured in Plate 3, figures 4—11. Occurring with them are frequently found typical specimens of *G. menardii*. Additional remarks on these forms will be found under *G. tumida*.

*G. menardii* is reported as rare to common (6—25 specimens) in the surface samples of two cores west of Newfoundland in the vicinity of Long. 40° W; on the continental shelf and slope of the northeastern United States south of Cape Cod from 0—5 % in most cases; in the Gulf of Mexico 5—10 %; east of Cuba 7 %; off the coast of Africa from Lat. 0° to 20° N±20 %. Brady gives a distribution in the Atlantic from 55° 11′ N to 51° 36′ S.

### Globorotalia multicamerata
Cushman and Jarvis
(Plate 3, figures 9, 12)

*Globorotalia menardi* (d'Orbigny) var. *mul*
*camerata* Cushman and Jarvis, 1930, Jou
Pal., vol. 4, no. 4, p. 367, pl. 34, fig. 8.

This species is described from the Mioce
of Buff Bay, Jamaica. The only report fro
the Recent is by Cushman and Bermud
(1949, p. 30) from 810 fms., north of Cu
The known range of the species is from t
Middle Miocene to the Recent, with all b
one of the reported occurrences from t
Miocene of Jamaica and Cuba.

### **Globorotalia punctulata** (d'Orbigny)
(Plate 4, figures 8, 9, 10, 11, 12)

*Globigerina punctulata* d'Orbigny, 1826, A
Sci. Nat., vol. 7, p. 277, no. 8. — Fornasi
1898, Paleont. Ital., vol. 4, p. 210, text. fig.

*Pulvinulina crassa* H. B. Brady (not *Rotali*
*crassa* d'Orbigny, 1840), 1884, Rep't. V
CHALLENGER, Zool., vol. 9, p. 694,
103, figs. 11, 12.

*Globigerina inflata* Cushman (not d'Orbig
1839), 1941, Amer. Journ. Sci., vol. 2
pl. 1, fig. 12.

*Globorotalia* (*Turborotalia*) *oceanica* Cushm
and Bermudez, 1949, Contr. Cushman L
Foram. Res., vol. 25, pt. 2, p. 43, pl.
figs. 13—15.

*Globorotalia hirsuta* Cushman and Bermu
(not d'Orbigny, 1839), ibid., p. 36, pl.
figs. 1—3.

*Globorotalia crassula* Ovey, in Wiseman
Ovey (not Cushman and Stewart, 19
1950, Proc. Geol. Assoc., vol. 61, pt. 1, p.
pl. 2, figs. 8 a—c.

*Globorotalia punctulata* (d'Orbigny), Phle
1951, Mem. 46, Geol. Soc. America, pt.
p. 68; Phleger and Parker, 1951, ibid.,
2, p. 36, pl. 20, figs. 3—7.

The above synonymy includes some var
forms which appear to us to belong to

ies group *G. punctulata*. It is of interest ote that four species have been erected authors who place Brady's »*Pulvinulina sa*» from the CHALLENGER Report in synonymy. These are:

*lobigerina crassaformis* Galloway and Wisser (Brady's pl. 103, figs. 11, 12). The type of his species has not been seen but it appears o be synonymous to our *G. punctulata*.

*loborotalia crassula* Cushman and. R. E. tewart (Brady's pl. 103, figs. 11, 12). he holotype is a very poor specimen which ppears to be referable to the *G. hirsuta* roup.

*loborotalia pseudocrassa* Chapman and Parr Brady's pl. 103, fig. 12 (not. fig. 11)). Ovey laces this species in the synonymy under is »*G. crassula*» which in turn we have ssigned to *G. punctulata*. He based this n specimens sent by Parr.

*loborotalia oceanica* Cushman and Bermulez (Brady's pl. 103, figs. 11, 12). The olotype is referable to *G. punctulata* and he species placed in the above synonymy.

he reasons for referring this species to *unctulata* (d'Orbigny) have been given in revious publication (Phleger and Parker, 1). This opinion has been strengthened by study of further material from Rimini ch contains specimens definitely referable l'Orbigny's species as exemplified by his res published by Fornasini. These specis are identical with those found in the th Atlantic.

his species, as was pointed out under *G. uta*, shows variations in the character of periphery from acute to subacute and the ons for not further subdividing it are the e as those given there. An example is the an form »*G. hirsuta*» of Cushman and Berlez, given in the above synonymy, which esents a variant with a very sharp periphery ch has been also observed in the Gulf of ico and is apparently not commonly found in the North Atlantic. Except for the acuteness of the periphery it is identical with the species as figured by Fornasini, Brady, and others, and does not seem to us to be specifically different.

*G. punctulata* is reported with a frequency of 0.4 % southwest of the British Isles; less than 5 % in the Gulf of Mexico; 0.1 % east of Cuba. The species referred to *G. crassa* by Schott (1935, p. 60), probably referable to *G. punctulata*, is found off the coast of Africa from Lat. 0° to 20° N with frequencies of ± 1 %. This is confirmed by the findings of Ovey at a station near the equator.

Brady reports the northern range of the species at Lat. 54° 53′ N.

### **Globorotalia scitula** (H. B. Brady)

(Plate 4, figures 13, 14)

*Pulvinulina scitula* H. B. Brady, 1882, Proc. Roy. Soc. Edinburgh, vol. 11, p. 716. — Balkwill and Millett, 1884, Journ. Micr., vol. 3, p. 85, pl. 4, fig. 12.

*Pulvinulina patagonica* H. B. Brady (not d'Orbigny, 1839), 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 693, pl. 103, fig. 7.

*Globorotalia scitula* (H. B. Brady), Cushman, 1931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 100, pl. 17, figs. 5 a—c. — Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, pt. 2, pl. 8, fig. 5. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 69, pl. 3, figs. 11 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 36, pl. 20, figs. 8, 9.

This species is reported with a frequency of 0.2 % southwest of the British Isles; as rare up to occurences of 6—26 specimens between this point and Newfoundland; at one station on the continental slope of the United States at close to Lat. 40° N; in the Gulf of Mexico less than 5 %; east of Cuba 0.2 %.

Brady gives a general distribution in the Atlantic from 60° N to 46° S.

### **Globorotalia truncatulinoides** (d'Orbigny)

(Plate 4, figures 17, 18)

*Rotalina truncatulinoides* d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, »Foraminifères», p. 132, pl. 2, figs. 25—27.

*Pulvinulina michelineana* H. B. Brady (not d'Orbigny, 1840), 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 694, pl. 104, figs. 1, 2.

*Globorotalia truncatulinoides* (d'Orbigny), Cushman, 1931, Bull. 104, U. S. Nat. Mus., pt. 8, p. 97, pl. 17, figs. 4 a—c; 1941, Amer. Journ. Sci., vol. 239, pl. 4, fig. 1. — Schott, 1935, Wiss. Ergeb. deutsch. Atlantisch. Exped. Forsch. Vermess. »Meteor» 1925—1927, vol. 3, pt. 3, Sect. B, p. 60. — Phleger, 1939, Bull. Geol. Soc. America, vol. 50, pl. 1, figs. 9, 10; — Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, pl. 7, figs. 12, 15. — Ovey, in Wiseman and Ovey, 1950, Proc. Geol. Assoc., vol. 61, pt. 1, p. 66, pl. 2, figs. 7 a—c. — Phleger, 1951, Mem. 46, Geol. Soc. America, pt. 1, p. 68; Phleger and Parker, 1951, ibid., pt. 2, p. 36, pl. 20, figs. 10—13.

This species is reported at 60° N Lat. with a frequency of 0.7 %; southwest of the British Isles 2 %; between this point and Newfoundland common to abundant; on the northeastern continental shelf and slope of the United States south of Cape Cod 0—1 %; in the Gulf of Mexico 10—20 %; east of Cuba 3 %; off Africa between Lat. 0° and 20° N ± 1 %. The highest frequencies have been reported from the Gulf of Mexico.

Brady gives the general distribution in the Atlantic from the Arctic 79° 26′ N to 46° 46′ S.

### **Globorotalia tumida** (H. B. Brady)

(Plate 3, figures 3, 6, 7, 8, 10, 11)

*Pulvinulina menardii* d'Orbigny var. *tumid* H. B. Brady, 1877, Geol. Mag., vol. 4, 294.

*Pulvinulina tumida* H. B. Brady, 1884, Rep' Voy. CHALLENGER, Zool., vol. 9, p. 69 pl. 103, figs. 4—6.

*Globorotalia tumida* (H. B. Brady), Cushma 1931, Bull. 104, U. S. Nat. Mus., pt. 8, 95, pl. 17, figs. 3 a—c. — Schott, 193 Wiss Ergeb. deutsch. Atlantisch. Expe Forsch. Vermess. »Meteor» 1925—1927, v 3, pt. 3, Sect. B, p. 60. — Cushman, 194 Amer. Journ. Sci., vol. 239, pl. 3, fig. — Phleger, 1939, Bull. Geol. Soc. Americ vol. 50, pl. 1, figs. 5—7; 1942, ibid., vo 53. — Parker, 1948, Bull. Mus. Com Zool., vol. 100, no. 2, pl. 7, figs. 16, 1 —Ovey, in Wiseman and Ovey, 1950, Pro Geol. Assoc., vol. 61, pt. 1, p. 69, pl. figs. 11 a—c. — Phleger, 1951, Mem. 4 Geol. Soc. America, pt. 1, p. 68; Phleg and Parker, 1951, ibid., pt. 2, p. 36, pl. 2 figs. 14, 15.

For the relationship between this speci and *G. menardii* see the remarks under th species. Typical *G. tumida* as figured by Bra and as seen in present day samples occu only in the upper sections of our cores a has been presumably only recently (geologica speaking) evolved from the so-called *menard tumida* complex occuring lower down in t cores. One interesting variant is that sho in pl. 3, figures 10, 11, in which the la formed chamber is narrow and sharply be toward the ventral side. This is listed on t charts in the *menardii-tumida* group since it hard to be certain to which species it belon although it perhaps shows a closer affinity *G. tumida*.

*G. tumida* is reported on the continen shelf and slope of the northeastern Uni States south of Cape Cod with frequencies

1 %; in the Gulf of Mexico 5 %; east of a 1 %; off the coast of Africa it has a uency of about 10 % at 20° N increasing the southwest to greater than 40 %, then reasing at Lat. 10° N to ± 1 %, and reasing to about 40 % near Fernando onka; to the east on the equator decreasing idly to ± 1 % and then increasing to 0 % near the African coast.

rady gives the distribution in the Atlantic n 38° 34′ N to 35° 39′ S.

### **Globorotalia** sp. 1

(Plate 4, figures 19, 20, 21)

his species is plano-convex, with a smooth, ished wall. The ventral side is very convex has a closed umbilicus. There are 3—4 mbers in the last-formed whorl.

he species is found in one sample near the tom of one core.

### **Globorotalia** sp. 2

(Plate 4, figures 15, 16)

his species resembles *G. menardii* in some pects but has a plano-convex test having 7 chambers in the last-formed whorl. It urs in cores containing fossil forms of own age, but appears higher than those cies in the cores.

pecimens of this form have been observed Middle Miocene Bowden Marl material m Jamaica.

### *Benthonic Species*

he benthonic species form a very small centage of the total faunas in both the face samples and the cores. In most cases was necessary to count all the benthonic cimens in a sample in an attempt to get adequate number for statistical analysis. en, however, this procedure did not yield sufficient quantity. For this reason the distributions of the various forms cannot be given with accuracy, except perhaps in the case of the more common and persistent ones. Absence of any species in a core, or at least in various parts of a core, does not mean that the species was non-existent at that particular time, or in that particular area. Much can be deduced, however, by noting occurrences in various cores in an area although almost nothing can be from the intermittent occurrences within a core. A notable exception to this is the occurrence of displaced faunas. Here analyses can be made on the basis of the occurrence or absence of whole groups of species based on an analysis of several cores containing representatives of these groups in varying amounts. These occurrences will be discussed in more detail later.

The scarcity of benthonic specimens also leads to another difficulty, that of taxonomic analysis. Many specimens occur in too small numbers to give an adequate picture of the range of variation of the species. It was often necessary to study suites composed of single specimens picked from various samples.

In spite of the scarcity of the benthonic forms one fact can be deduced with considerable accuracy. This is that most deep-water benthonic forms have a wide range of occurrence, being found throughout the area. Many of these same species are also found in the deep waters of the Pacific and appear to be almost universally present in deep water where Foraminifera are found. Whether or not this is due to the essentially uniform temperature of the deep layers is an interesting problem.

There is a considerable number of arenaceous species found in the surface samples, more rarely in the »top» samples of the long cores. These species are found very rarely in the cores below the »top». They have not been listed separately in Table 38, giving species occurrence in the surface samples, because of the doubtful value of such information. They are listed as a group, however, since in aggregate they often form a relatively high percentage of the benthonic fauna. Since these species are not included in the species discussions a brief discussion follows. The species having the most widespread occurrence in the area is *Adercotryma glomeratum* (H. B. Brady), occurring in 23 of the 53 surface samples. Other species of interest are: *Cystammina galatea* (H. B. Brady), found in 10 samples; *C. pauciloculata* (H. B. Brady), in 7 samples; *Proteonina difflugiformis* (H. B. Brady) in 11 samples. Various specimens of *Recurvoides*, *Cyclammina*, *Reophax* and *Trochammina* occur in small quantities in many samples but not in a sufficient number for safe identification. In addition there are very rare occurrences of several additional species. It is interesting to speculate on the reasons for the usual absence of these species in the cores, below the top. One explanation is that the cementing material is weakened by solution; another that many of the species are very fragile and easily broken and may not be able to withstand compaction.

A study of displaced faunas in several cores has resulted in the formation of a list of what are believed to be reliable key species indicative of displacement from comparatively shallow depths. A second list of species contains forms that are questionably related to the displaced faunas, since they have occasionally been found in other cores where displacement cannot be established, but where, nevertheless, it may be present. The method of establishing the presence and especially the extent of these faunas may be of interest since all the species involved have not come from very shallow depths. The faunas containing such known shallow-water species as *Amphistegina lessonii*, *Rotalia beccarii* variants and various species of *Elphidium* were first analyzed and the associated species noted. The occurrences of these allied species were then studied and where they were noted in discrete assemblages the faunas were again analyzed. By this proc it was possible to weed out the known dee water forms leaving a residue of forms th were probably present due to transportati These species, then, are only found in asso ation with each other and not apparen disseminated indiscriminately through t cores. In the case of a few of the species a f exceptions in occurrence are noted where the is not enough evidence for displacement the presence of a sufficient number of the species. This does not rule out the possibili of there being displacement in those pa ticular cases, however. Further discussion the whole problem and the actual occurren in the various cores is given elsewhere.

The following species appear to be displac forms. Their previously reported depth occu rences are given, many of which are tak from Brady's report on the CHALLENGE Expedition and may include displaced occu rences. Where possible more precise informati is given from various sources.

*Anomalina balthica* Schroeter: less than 3,000

*Amphistegina lessonii* d'Orbigny: 0—90 (in most cases)

*Angulogerina selseyensis* (Heron-Allen and Ea land): shallow water off Cuba; Selsey, En land, shore sand

*Bolivina globulosa* Cushman: (1 exceptio less than 5270 m. in tropical Pacific

*B. paula* Cushman and Cahill: Miocene (sha low facies?)

*B. pseudoplicata* Heron-Allen and Earlan less than 90 m. except in Skagerak where is most common at 200 m.

*B. pulchella* (d'Orbigny): less than 1,500

*B. subaenariensis* Cushman: (1 exceptio 155—2,981 m. (H. B. Brady); less than 1,0 m. (Phleger)

*B. tortuosa* H. B. Brady: mostly shallow wat

*B.* sp. 1

*Bulimina exilis* H. B. Brady: 1,829—2,743 (H. B. Brady) *marginata* d'Orbigny var.: less than 2,981 . (H. B. Brady)

*mexicana* Cushman: 80—2,430 m.

aff. *subacuminata* Cushman and R. E. tewart: deeper than 670 m. in Pacific off alifornia

*icris* cf. *oblonga* (Williamson): less than 00 m.

*ssidulina curvata* Phleger and Parker: deeper han 90 m. (Gulf of Mexico)

*norcrossi australis* Phleger and Parker: 00—700 m. (Gulf of Mexico)

sp. 1

*ssidulinoides mexicana* (Cushman): 40 m. ff Florida; 1,488 m. in Caribbean

*icides* cf. *refulgens* Montfort: 82—4,390 m.

*icidina rhodiensis* (Terquem): 30—512 m. Red Sea)

*rnuspira planorbis* Schultze: no definite data

*scorbis bertheloti* (d'Orbigny): 0—650 m.

cf. *columbiensis* Cushman: shallow

*mamilla* (Williamson): shallow

*obtusa* (d'Orbigny): no conclusive data

*phidium advenum* (Cushman): shallow

*complanatum* (d'Orbigny): 100—200 m. (off oast of Africa)

*crispum* (Linné): less than 726 m.; usually ess than 300 m.

*nion asterizans* (Fichtel and Moll): 9—322 m.; usually less than 100 m.

*nionella sloanii* (d'Orbigny): described from shore sands of Cuba; little additional data

sp.

*anorbulina mediterranensis* d'Orbigny: less than 1,160 m.; usually less than 150 m.

*llenia* cf. *riveroi* Bermudez: less than 1,042 m. based on rather sparse data

*ctuvigerina* sp.

*otalia» beccarii* (Linné) variants: shallow

*.» translucens* Phleger and Parker: 25—1,000 (Gulf of Mexico)

*etomphalus atlanticus* Cushman: shallow (West Indies)

*Uvigerina senticosa* Cushman: less than 500 m. off California

*U.* sp. 1

*U.* sp. 2

*Valvulineria araucana* (d'Orbigny): 80—160 m. in most cases

*Virgulina mexicana* Cushman: 110—1,350 m. (Gulf of Mexico)

*V. tessellata* Phleger and Parker: less than 1,000 m. (Gulf of Mexico)

The following species are questionably displaced forms. They have been found in a few cases associated with assemblages that cannot necessarily be considered as displaced.

*Bolivina* cf. *minuta* Natland: deeper than 274 m. off California

*Bulimina aculeata* d'Orbigny: 100—2,800 m. in most cases

*Cibicides lobatulus* (Walker and Jacob): widespread reports

*Discorbis williamsoni* Parr: 0—1,860 m.; mostly less than 100 m.

*Nonionella atlantica* Cushman: less than 200 m. (Gulf of Mexico); usually less than 70 m.

*Nummoloculina irregularis* (d'Orbigny): deeper than 640 m.

*Ophthalmidium inconstans* H. B. Brady: widespread reports

*Rotamorphina laevigata* (Phleger and Parker): deeper than 300 m.

*Trochammina* cf. *advena* Cushman: less than 1,850 m.; usually less than 60 m.

Benthonic species of possible Miocene age occur in Cores 233 and 238. They are in both cases associated with planktonic species also of probable Miocene age. The benthonic species are: *Buliminella* sp., *Cassidulina reflexa* Galloway and Wissler and *Bolivina* sp. 2. Further discussion of these species is given in the section on the interpretation of the core faunas and in the species discussions.

For convenience in presenting the taxonomic material, Cushman's classification is used; in many cases the types have been seen at the

U. S. National Museum in Washington, D. C., and in many other cases topotype material has been studied. Distributions in the North Atlantic as reported in the literature are given together with the distributions observed in this study.

## Family AMMODISCIDAE

### **Glomospira charoides** (Jones and Parker)

(Plate 5, figure 1)

*Trochammina squamata* var. *charoides* Jones and Parker, 1 860, Quart. Journ. Geol. Soc., vol. 16, p. 304.

*Trochammina charoides* Jones and Parker, Carpenter, Parker and Jones, 1 862, Introd. Foram., p. 141, pl. 11, fig. 3.

This species is reported from depths greater than 200 m. It occurs rarely in Cores 228, 234, and 246.

### **Glomospira** cf. **gordialis** (Jones and Parker)

(Plate 5, figure 2)

*Trochammina squamata* var. *gordialis* Jones and Parker, 1 860, Quart. Journ. Geol. Soc., vol. 16, p. 304.

*Trochammina gordialis* Jones and Parker, Carpenter, Parker and Jones, 1,862, Introd. Foram. p. 141, pl. 11, fig. 4.

A few specimens occur having a smooth, polished test. In other respects they are similar to Jones and Parker's species, which is widely distributed, with most reported occurrences from deep water. It occurs in Cores 217, 242, 246, and 267, and from surface samples 225, 235, 267, 281, 283, and REHOBETH Sta. 3—29 and 3—41.

## Family TEXTULARIIDAE

### **Textularia australis** Parr

(Plate 5, figures 3, 4)

*Textularia australis* Parr, 1950, B. A. N. Z. Antarctic Res. Exped. 1929—1931, Ser. B, vol. 5, pt. 6, p. 275, pl. 4, figs. 30 a—c.

North Atlantic specimens resemble Parr's except for their smaller size, the maximum length being 0.9 mm., the average length 0.7 mm. The species is not reported from the Atlantic. It occurs widely in the cores and in surface samples 236, 252, 257, 258, and ATLANTIS Sta. 4,637, 4,736, and 4,739.

### **Siphotextularia curta** (Cushman)

(Plate 5, figures 5, 6)

*Textularia flintii* var. *curta* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 14, pl. 2, figs. 2, 3.

North Atlantic specimens are identical with the types. Cushman reports the species from the Caribbean, deeper than 406 m. It is probable that it is also reported under other names but this cannot be confirmed. The species occurs in Cores 221, 267, 288, 290, and in surface sample ATLANTIS Sta. 4,631.

### **Siphotextularia rolshauseni**
### Phleger and Parker

(Plate 5, figure 7)

*Siphotextularia rolshauseni* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 4, pl. 1, figs. 23, 24 a, b.

*Textularia catenata* Cusman 1922 (not Cushman, 1911), Bull. 104, U. S. Nat. Mus., pt. 3, p. 12, pl. 6, fig. 3.

North Atlantic specimens are larger than those from the Gulf of Mexico with an average length of 0.5 mm. They are also slightly more compressed. Cushman's plesiotype of *S. catenata* from the Atlantic is identical but the North Atlantic species does not resemble the holotype of that species described from the Pacific, which, from the description, is a much larger form. It is possible that the Atlantic forms represent a subspecies of *S. rolshauseni* but the two forms are undoubtedly very closely related. The species is widely distributed in the cores and surface samples.

## Family VALVULINIDAE

### **Eggerella bradyi** (Cushman)

(Plate 5, figures 8, 9)

*erneuilina bradyi* Cushman, 1911, Bull 71, U. S. Nat. Mus., pt. 2, p. 54, text figs. 87 a, b.

*erneuilina pygmaea* H. B. Brady (not *Bulimina pygmaea* Egger, 1857), 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 385, pl. 47, figs. 4—7.

Adult specimens of this species may have a ry short biserial stage. For this reason it ight be more accurate to designate the species *Karreriella.* Inasmuch, however, as the great ajority of specimens do not reach this stage seems more expedient to keep the species in e genus *Eggerella.* This expediency is further nphasized by the fact that there is already a ecies *Karreriella bradyi* (Cushman) which referred to extensively in the literature of oth fossil and Recent material. As »*Verneuil- a bradyi*» has priority over »*Gaudryina bradyi*», e original name of *Karreriella bradyi,* a fferent interpretation of *K. bradyi* would use great confusion. Specimens of this species om PORCUPINE Sta. 36, close to Brady's cality of the figured CHALLENGER speci- ens of his »*Gaudryina pupoides* d'Orbigny» hich Cushman renamed, show a small form ith a long biserial series of slightly overlapping ambers. Similar forms occur in the Gulf Mexico, the West Indies and elsewhere, but e not found except for questionable very re occurrences in the North Atlantic material. *ggerella bradyi,* which is very common in the orth Atlantic, is usually larger although ere is great variation in size. The specimens owing the very short biserial stage are often e same size as *K. bradyi.* Young forms of the o species are probably very difficult to dif- rentiate and for this reason many reports of *ggerella bradyi* may be referable to *Karreriella adyi.*

This applies especially to the very small specimens in the *Eggerella* stage of development which are frequently seen without adult specimens. It seems probable that most of these forms in the North Atlantic material are referable to *E. bradyi* since so few *Karreriella bradyi* adult specimens are seen. The depth range of *K. bradyi* appears to be less extensive and it is probably limited to depths of 155—1,326 m., although Brady reports it deeper. *Eggerella bradyi* is reported deeper than 600 m. The species shows a range of variation in the character of the wall from smooth, polished to slightly roughened but there is in all cases a large quantity of calcareous cement. The species is widely distributed in the cores and surface samples.

### **Plectina apicularis** (Cushman)

(Plate 5, figure 10)

*Gaudryina apicularis* Cushman, 1911, Bull. 71, U. S. Nat. Mus., pt. 2, p. 69, text figs. 110 a, b.

This species is reported from the North Atlantic usually deeper than 700 m. and from the Gulf of Mexico deeper than 200 m. It is widely distributed in the surface samples and also occurs at the top, or near the top, in about ten scattered cores. The deepest occurrence in the cores is at 210 cm. in Core 217.

## Family MILIOLIDAE

### **Quinqueloculina venusta** Karrer

(Plate 5, figures 11, 12)

*Quinqueloculina venusta* Karrer, 1868, Sitz. k. Akad. Wiss. Wien., vol. 58, Abth. 1, p. 147, pl. 2, fig. 6.

This species is reported deeper than 3292 m. It is widespread in the cores and surface samples.

### **Quinqueloculina** cf. **weaveri** Rau

(Plate 5, figures 13, 14)

*Quinqueloculina weaveri* Rau, 1948, Journ. Pal., vol. 22, no. 2, p. 159, pl. 28, figs 1—3.

This species is very similar to Rau's except that the periphery is slightly less rounded and the chambers are slightly angled. The character of the aperture is very similar and in both forms there is no tooth, an unusual feature. Most of the North Atlantic specimens are smaller than Rau's species, described from the Porter shale of Washingron, probably upper Eocene in age. It is widely distributed in the North Atlantic in both cores and surface samples.

### **Spiroloculina** sp.

(Plate 5, figures 15, 16)

This species resembles *Spirolocammina tenuis* Heron-Allen and Earland but has a calcareous test which is entirely destroyed by acid, except for a thin, chitinous inner layer. Rare occurrences are found in scattered cores throughout the area, except in the cores along the South American coast, and in surface samples 285, 289, 292, and ATLANTIS Sta. 4635 and 4637.

### **Sigmoilina schlumbergeri** A. Silvestri

(Plate 5, figure 17)

*Sigmoilina schlumbergeri* A. Silvestri, 1904, Mem. Pont. Accad. Nuovi Lincei, vol. 22, p. 267.

This species is reported deeper than 80 m. It is found in cores south of Lat. 25° N along the African coast, in Core 267 and in the group from 289—296. It also occurs in surface samples in these same areas.

### **Sigmoilina tenuis** (Czjzek)

(Plate 5, figure 18)

*Quinqueloculina tenuis* Czjzek, 1848, Haidinger's Nat. Abhandl., vol. 2, p. 149, pl. 13, figs. 31—34.

North Atlantic specimens are slightly more compressed, with slightly narrower chamber than those from the Miocene at Baden in the Vienna Basin. They are otherwise very similar The species is reported from the Bay of Naples deeper than 200 m. It is found in many cores from 215—252 along the Coast of Africa and in the southern part of the area, and in the northern group of cores 279—296. It occurs in only two surface samples, at ATLANTIS Sta. 4637 and 4736.

### **Nummoloculina irregularis** (d'Orbigny)

(Plate 5, figures 19, 20)

*Biloculina irregularis* d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, »Foraminifères», p. 67, pl. 8, figs. 20, 21.

Brady (1884, p. 140) reports this species from a few stations in the mid-latitudes deeper than 640 m. It occurs associated with displaced faunas in Cores 215, 221, 252, 258, 267, and in a questionably displaced fauna in Core 246. It is found in surface samples 267 and ATLANTIS Sta. 4631.

### **Triloculina tricarinata** d'Orbigny

(Plate 5, figure 21)

*Triloculina tricarinata* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 299, no 7; Modèles no. 94.

This species has a very wide distribution according to the reports in the literature. It is found in scattered cores from Cores 242—258, in Core 267 and in many of the northern group 284—296. It occurs in three surface samples: 267, REHOBETH Sta. 3—32 and SAN PABLO Sta. 3—47.

### **Pyrgo murrhina** (Schwager)

(Plate 5, figures 22, 23, 24)

*Biloculina murrhina* Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 203, pl. 4, figs. 15 a—c.

This species varies a great deal in size and shape. The characteristic sinus at the ower end of the test, with its two projecting oints, is often lacking in adult specimens. Iany report of *P. depressa* (d'Orbigny) in- lude specimens of this type. The aperture of 'Orbigny's species is very different, however, eing a very elongate, narrow slit near the pex of the test. The aperture of *P. murrhina* aries in breadth, being much less broad in ıvenile specimens. It is reported deeper than 00 m. in the North Atlantic but has its highest equency between 100—200 m. in the north- estern Gulf of Mexico. It is widely distributed ı the cores and surface samples.

### **Pyrgo oblonga** (d'Orbigny)

(Plate 5, figures 25, 26)

*iloculina oblonga* d'Orbigny, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foram- inifères», p. 163, pl. 8, figs. 21—23.

The prolongation of the neck and the angle the periphery vary in this species. The eriphery may be rounded to carinate, suites specimens showing a transition from the vo extremes. d'Orbigny's figure illustrates ıe form with rounded periphery. In most ıses the apertural neck is longer than that ıown in his figure, but specimens identical to s occur. Some of the reports of *P. elongata* 'Orbigny) may be referable to *P. oblonga*, hich is widely distributed in the cores and ccurs in surface samples ATLANTIS Sta. '36, and REHOBETH Sta. 3—29.

## **Family OPHTHALMIDIIDAE**

### **Cornuspira planorbis** Schultze

(Plate 5, figure 30)

*ornuspira planorbis* Schultze, 1854, Organis- mus Polythal., p. 40, pl. 2, fig. 21.

This species is rare. It occurs in Cores 228, 8, 252, and 267.

### **Ophthalmidium inconstans** (H. B. Brady)

(Plate 5, figure 27)

*Ophthalmidium inconstans* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 189, pl. 12, figs. 5, 7, 8. (*Haverina inconstans* Brady, 1879).

This species is widely reported in the North Atlantic. It occurs in Cores 248, 267, 289, and in surface sample ATLANTIS Sta. 4631.

### **Spirophthalmidium acutimargo** (H. B. Brady)

(Plate 5, figures 28, 29)

*Spiroloculina acutimargo* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 154, pl. 10, fig. 13 (not figs. 12, 14, 15).

The reported distribution in the North Atlantic is confused by the inclusion of more than one species. *S. acutimargo* is reported off the coast of Ireland in 170 m. It occurs in Cores 228, 236, 267 and 288.

## **Family TROCHAMMINIDAE**

### **Trochammina** cf. **advena** Cushman

(Plate 6, figures 1, 2)

*Trochammina advena* Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 20, pl. 1, figs. 2—4.

A few specimens occur in Core 267, most of which resemble the holotype. One specimen is much larger, reaching a diameter of 0.54 mm. The species is reported from the Tortugas region, off Florida, from 9—19 m. In the Gulf of Mexico it is most frequent shallower than 60 m. but occurs to a depth of 1850 m.

## **Family NONIONIDAE**

### **Nonion asterizans** (Fichtel and Moll)

(Plate 6, figure 3)

*Nautilus asterizans* Fichtel and Moll, 1798, Text. Micr., p. 37, pl. 3, figs. e—h.

North Atlantic specimens are identical with topotypes from Rimini, Italy, and are also very much like topotypes of *N. boueanum* (d'Orbigny) from the Miocene of Nussdorf in the Vienna Basin. From the few specimens examined the two species appear to be synonymous but a study of larger suites may show statistical differences. This has also been pointed out by Marks (1951, p. 48). The form reported by Colom (1950, p. 26) off the coast of Bojador, Africa, as *N. boueanum* is undoubtedly our species. He reports it as common to frequent from 9—100 m. and infrequent to a depth of 322 m. A few specimens occur in Core 221, associated at least in part with a displaced faunal assemblage.

### **Nonion barleeanum** (Williamson)

(Plate 6, figure 4)

*Nonionina barleeana* Williamson, 1858, Rec. Foram. Great Britain, p. 32, pl. 3, figs. 68, 69.

This species is allied to *N. pompilioides* (Fichtel and Moll) and *N. formosum* (Seguenza). It is more compressed than most specimens of *N. pompilioides* and has more limbate sutures which fuse into a very much thickened ring of clear shell material at the umbilicus. The last-formed whorl seldom has less than 10 chambers and often more. *N. formosum* has narrow sutures, fewer chambers, and non-limbate sutures without the central ring of fused material. The three species are variable but can be easily separated once the main characteristics are understood. There has been too much confusion within this group to give the reported distribution accurately. This species is widely distributed in the cores and occurs in widely scattered surface samples.

### **Nonion formosum** (Seguenza)

(Plate 6, figure 5)

*Nonionina formosa* Seguenza, 1880, Atti R. Accad. Lincei, ser. 3, vol. 6, p. 63, pl. 7, figs. 6, 6 a.

North Atlantic specimens are identical wi topotypes from the Tertiary of Calabria, Ita See *N. barleeanum* for a comparison with th species. *N. formosum* is more compressed th *N. pompilioides*, more finely perforate, a usually has a closed umbilicus. The fo recorded by Cushman and Henbest (1940, pl. fig. 13) as *N. barleeanum* should be referred this species, which has not been recorded such from the Recent. It is widely distribut in the cores and surface samples.

### **Nonion germanicum** (Ehrenberg)

(Plate 6, figure 6)

*Nonionina germanica* Ehrenberg, 1839, Abhand k. Akad. Wiss. Berlin, p. 133, pl. 2, figs. 1 a—

Ehrenberg records this species from th North Sea. Williamson (1858, p. 33, pl. 3, fig 70, 71) records it as *N. crassula* (Walker an Jacob) in the vicinity of the British Isles. It widely distributed in the cores and occurs scattered surface samples mostly in the souther part of the area with the exception of REH BETH Sta. 3—29.

### **Nonion pompilioides** (Fichtel and Moll)

(Plate 6, figures 7, 8)

*Nautilus pompilioides* Fichtel and Moll, 179 Test. Micr., p. 31, pl. 2, figs. a—c.

This species rarely has more than 9 chambe in the last whorl. It is more coarsely perfora than *N. barleeanum* and more deeply umbilica without the greatly thickened ring around th umbilicus. Some of the large, less-compresse specimens of *N. barleeanum* are difficult t separate from this form and it is necessary t have a good sequence of specimens for stud Both species apparently occur in the Mediter ranean and it is probable that many form referred to *N. pompilioides* should be referre to *N. barleeanum*. The characteristics of Ficht and Moll's species are well illustrated b specimens from the Pliocene of Coroncina, Ital here they reported its occurrence. It is teresting to note that associated with this ecies at that locality there is a species closely lated to *N. barleeanum*. The two species are pparently frequently associated as is found be the case in the North Atlantic where . *pompilioides* is widely distributed in both res and surface samples.

### **Nonionella atlantica** Cushman

(Plate 6, figures 9, 10)

*onionella atlantica* Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 4, 5.

This species is reported off Florida and in the rthwestern Gulf of Mexico at depths shallower an 200 m., with the highest frequency allower than 70 m. It is associated with splaced faunal assemblages in Cores 257, 258, d 262, and with questionably displaced unas in Cores 233 and 242.

### **Nonionella sloanii** (d'Orbigny)

(Plate 6, figures 11, 12)

*nionina sloanii* d'Orbigny, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 46, pl. 6, figs. 18, 18 bis.

d'Orbigny describes this species from shore nds of Cuba. Our specimens are identical th Cuban specimens and are referable to the nus *Nonionella*. The species is associated th displaced faunal assemblages in Cores 3, 252, 257, and 267.

### **Nonionella** sp.

(Plate 6, figures 13, 14)

This is a smaller, less compressed, less turgid m than *N. opima* Cushman. It has 8 slightly lated chambers and a small lobe. It occurs Core 252 associated with a displaced faunal emblage. It is assumed to be a shallow water cies since species of this type do not appear be indigenous to deep water environments.

### **Elphidium advenum** (Cushman)

(Plate 6, figure 15)

*Polystomella advena* Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 56, pl. 9, figs. 11, 12.

This species is reported only from shallow water. It is associated with displaced faunal assemblages in Cores 221, 228, 252 and 267.

### **Elphidium complanatum** (d'Orbigny)

(Plate 6, figure 16)

*Polystomella complanata* d'Orbigny, in Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, »Foraminifères», p. 129, pl. 2 figs. 35, 36.

This species is very similar to d'Orbigny's figured specimens except that it has a slight keel. He describes the species as having a diameter of 0.33 mm. The largest of our specimens has a diameter of 0.68 mm. A specimen identical with ours has been found in material from CHALLENGER Sta. 8 off Gomera in the Canary Islands. Colom (1950, p. 27, pl. 9, figs. 10, 11) has similar specimens which he refers also to *E. complanatum*. His species, too, has a keeled periphery. Colom's material came from close to the Canaries off the coast of Africa at Bojador. Under the circumstances it seems safe to assume that d'Orbigny overlooked the slight keel since his figure agrees closely in other repects. Colom reports the species in his 100—200 m. facies. The specimens he figures on his plate 3 b are apparently referable not to this species but to *E. crispum*.

### **Elphidium crispum** (Linné)

(Plate 6, figure 17)

*Nautilus crispus* Linné, 1758, Syst. Nat. ed. 10, p. 709.

A study of specimens from Rimini, Italy, shows that there is probably no specific difference between *E. crispum* and *E. macellum*

(Fichtel and Moll). All gradations may be seen between the two forms. Most of the specimens found in the cores are of the *E. macellum* type, with a small umbo and about 20 chambers or less in the last-formed whorl. This may be due to the fact that all the specimens are relatively small. Colom (1950, p. 27) reports *E. crispum* in abundance off the coast of Bojador, Africa, out to a depth of 300 m., with occasional occurrences to a depth of 726 m. It occurs associated with displaced faunal assemblages in Cores 215 and 221 off the coast of Africa.

## Family BULIMINIDAE

### **Buliminella** sp.

(Plate 6, figure 18)

A few specimens occur in Core 233 at 801 cm. and below. The species has not been described but specimens have been observed in Oligo-Miocene material from Haiti collected by W. P. Woodring. The specimens are very short and broad and are decorated with irregular costae. Fine radiating grooves extend from the aperture which is in a sunken area near the apex of the test.

### **Robertina bradyi** Cushman and Parker

(Plate 6, figures 19, 20)

*Robertina bradyi* Cushman and Parker, 1936, Contr. Cushman Lab. Foram. Res., vol. 12, pt. 4, p. 99, pl. 16, figs. 9 a, b.

This species was described from the Caribbean at a depth of 698 m. It occurs in Cores 221, 223, 246, 267 and 288. The reasons for retaining this species in the genus *Robertina* are given by Parker (1952, p. 416).

### **Bulimina aculeata** d'Orbigny

(Plate 6, figures 21, 22)

*Bulimina aculeata* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 7.

*Polymorphia pineiformis* Soldani (part), 1791, Test., vol. 1, pt. 2, p. 118, pl. 127, fig. 1?; pl. 130, fig. *vv*.

Most records in the North Atlantic are from depths between 100 m. and 2800 m. The species is associated with displaced faunas in many of the southern group of cores listed as containing these faunas. It also occurs in Cores 280, 288, 289, 290 and 292 in the northern group and in surface samples 224, and SAN PABLO Sta. 3—47. Whether or not its presence indicates displacement in all cases is open to question.

### **Bulimina alazanensis** Cushman

(Plate 6, figure 23)

*Bulimina alazanensis* Cushman, 1927, Journ. Pal., vol. 1, p. 161, pl. 25, fig. 4.

This species is reported in the Gulf of Mexico from 400—1800 m. No data is given on depths in the North Atlantic but it is reported from the West Indies and near Ireland. It has a widespread occurrence in the cores and surface samples.

### **Bulimina exilis** H. B. Brady

(Plate 6, figure 24)

*Bulimina elegans* d'Orbigny var. *exilis* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 399, pl. 50, figs. 5, 6.

Brady reports this species in the North Atlantic from 1829—2743 m. Parker (1948, p. 225) reports it at shallower depths on the western continental slope with a minimum depth of 359 m. This corroborates Cushman's findings in the same general area (1922, p. 106). Heron-Allen and Earland (1916, p. 234) report it from very shallow depths west of Scotland. It is associated with displaced faunal assemblages in Cores 221, 252, 257, 258 and 262 and occurs in the top sample of Core 280, which questionably contains displaced forms.

### **Bulimina marginata** d'Orbigny variant

(Plate 6, figures 25, 26)

*ulimina marginata* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 4, pl. 12, figs. 10—12.

Occasional specimens are found which are naller and usually less spinose than the Rimini ecimens figured by d'Orbigny. *B. marginata* recorded from a wide range of depths. Brady 884, p. 405) reports its deepest occurrence at 981 m. and it is also frequently reported in ery shallow water. If a sufficient number of ecimens could be obtained from deep water r statistical analysis they might show specific ifferences from the shallow water form. The ariant found by Parker (1948, p. 225) in the eeper part of the continental shelf and adjacent ope of the western Atlantic is unlike the resent variant in being very spinose. This rm is associated with displaced faunal assemlages in Cores 221, 228, 252, 257, 258 and 262.

### **Bulimina mexicana** Cushman

(Plate 6, figure 27)

*ulimina inflata* Seguenza var. *mexicana* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 95, pl. 21, fig. 2.

This species is reported from mid latitudes the North Atlantic from 80—2,430 m. It associated with displaced faunal assemblages Cores 215, 221, 252 and 267. It also occurs Core 290.

### **Bulimina** aff. **subacuminata** Cushman and R. E. Stewart

(Plate 6, figures 28, 29)

*ulimina subacuminata* Cushman and R. E. Stewart, 1930, in Cushman, Stewart and Stewart, San Diego Nat. Hist. Trans., vol. 6, no. 2, p. 65, pl. 5, figs. 2, 3 a, b.

North Atlantic specimens are very similar Cushman and Stewart's species but the stae are slightly finer and do not extend so far up onto the chambers. The species is not reported from the Atlantic but is found deeper than 670 m. off the coast of California. It is associated with a displaced faunal assemblage in Core 221.

### **Bulimina translucens** Parker, n. sp.

(Plate 6, figures 30, 31)

Test small, slender, gradually tapering from the widest point at the midpoint of the last-formed whorl, megalospheric form about twice as long as broad, microspheric three times, initial end rounded, the microspheric form with six or seven whorls, the megalospheric about five; chambers distinct, slightly inflated, increasing gradually in size as added; sutures distinct, slightly depressed; wall smooth, tinely perforate, translucent, the lower part of fhe test often, not always, decorated by a few low, curving costae which extend as much as halfway up the test, aperture moderately broad, loopshaped, above the junction of the second and third chambers, near the apex of the test. Maximum length 0.44 mm.; maximum width 0.2 mm.

The holotype is from ATLANTIS Sta. 4637, Lat. 35° 22′ N, Long. 10° 23′ W, at a depth of 4,181 m.

The dimensions given above are for large specimens but many are much smaller with a length of about 0.3 mm. The larger specimens are almost invariably decorated with the costae; the proportion of the smaller ones so decorated is less. Frequently the costae are so low and translucent that it is difficult to detect them. This species most closely resembles *B. thanetensis* Cushman and Parker but is much more finely perforate and is usually costate on the lower part of the test. The chambers are less inflated than in *B. elongata* d'Orbigny. The species occurs in Cores 242, 246, 248, 252, 257, 258, 284, and in surface samples 284 and ATLANTIS Sta. 4637.

### **Globobulimina affinis** (d'Orbigny)

(Plate 6, figure 32)

*Bulimina affinis* d'Orbigny, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 105, pl. 2, figs 25, 26.

This species is reclassified as a *Globobulimina* in accordance with Höglund's (1947, p. 237) revision of the generic description. The structure of the aperture and tongue accords with his definition, as well as the less densely perforate wall. The species is reported from the Atlantic from deeper than 97 m. It occurs in Cores 258 and 288.

### **Globobulimina (Desinobulimina)** cf. **turgida** (Bailey)

(Plate 6, figures 33, 34)

*Bulimina turgida* Bailey, 1851, Smithsonian Contr., vol. 2, p. 12, pl., figs. 28—31.

The North Atlantic specimens are similar to Bailey's except that they are not always spinose. Höglund (1947, p. 248) found that his specimens of this species did not have a terminal aperture without a suture, but specimens from the Atlantic continental shelf have this feature although not as frequently as do specimens of *G.* (*D.*) *auriculata* (Bailey). *G.* (*D.*) *turgida* is reported from the western Atlantic continental shelf deeper than 90 m. and from the Skagerak as abundant from 200—300 m., being rare at deeper or shallower stations. The species occurs in Cores 221, 223, 233 and surface samples 224 and 225.

### **Virgulina advena** Cushman

(Plate 7, figures 1, 2)

*Virgulina* (?) *advena* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 120, pl. 25, figs. 1—3.

Cushman questioned the genus of this form when he described it. Although the narrow aperture extending over the apex of the test is an unusual feature of the genus, the internal structure of the aperture is very similar to that of other species of the genus. The only apparent dissimilarity is that the tongue extending inward from the border of the aperture is only slightly curving and does not bend back toward the free apertural border. The species is reported deeper than 236 m. It is widespread in the cores except along the coast of South America north of Lat. 34° N in the western part of the area. It is found in surface samples 285 and SAN PABLO Sta. 3—47.

### **Virgulina bradyi** Cushman

(Plate 7, figures 4, 5)

*Virgulina bradyi* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 115, pl. 24, fig. 1.

This species is reported in the North Atlantic deeper than 258 m. It is widely distributed in the cores and occurs in surface samples 224, 225, 230, 234 and REHOBETH Sta. 3—38.

### **Virgulina complanata** Egger

(Plate 7, figure 3)

*Virgulina schreibersiana* Czjzek var. *complanata* Egger, 1893, Abhandl. k. bay Akad. Wiss. München, Cl. II, vol. 18, p. 292, pl. 8, figs. 91, 92.

In the Gulf of Mexico this species is most abundant at depths of less than 1,000 m. It is also found on the western Atlantic continental shelf and slope. It is widely distributed in the cores and occurs in surface samples 224, 258 and ATLANTIS Sta. 4,637.

### **Virgulina mexicana** Cushman

(Plate 7, figures 6, 7)

*Virgulina mexicana* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 120, pl. 23, fig. 8.

This species is reported from the Gulf of Mexico deeper than 90 m. Brady (1884, p.

415, pl. 52, figs. 10, 11 (not 7, 8, 9) ) reports it as *V. subsquammosa* (part) in the North Atlantic, but its distribution cannot be separated from that of the other species that he includes under that name. *V. mexicana* is associated with displaced faunal assemblages in Cores 221, 248, and 252.

### **Virgulina tessellata** Phleger and Parker

(Plate 7, figure 8)

*Virgulina tessellata* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 19, pl. 9, figs. 15 a, b, 16 a, b.

This species is reported as rare in the northwestern Gulf of Mexico shallower than 1,000 m. It is associated with displaced faunal assemblages in Cores 248 and 252.

### **Virgulina** sp.

(Plate 7, figures 9, 10)

This is a small, translucent species which somewhat resembles *V. tessellata* in having the lower part of the chambers perforate. It is more rapidly tapering than that species and does not have contrasting opaque and translucent areas on the chambers. It occurs in Cores 246, 248 and 284.

### **Bolivina globulosa** Cushman

(Plate 7, figure 11)

*Bolivina globulosa* Cushman, 1933, Contr. Cushman Lab. Foram. Res., vol. 9, pt. 4, p. 80, pl. 8, figs. 9 a, b.

North Atlantic specimens are identical with the holotype. The species is reported from deep water in the tropical Pacific but not from the Atlantic. It is associated with shallow-water displaced faunal assemblages in Cores 242, 248, 252 and 267 off St. Croix and in the equatorial region.

### **Bolivina** cf. **minuta** Natland

(Plate 7, figure 12)

*Bolivina minuta* Natland, 1938, Bull. Scripps Instit. Ocean., Techn. Ser., vol. 4, no. 5, p. 146, pl. 5, fig. 10.

*Bolivina* sp. (?) Cushman and Henbest, 1940, Prof. Paper 196—A, U. S. Geol. Surv., pt. 2, pl. 9, fig. 24.

Most of the specimens are thicker, with more highly raised sutures than Natland's species, but include in their range of variation specimens very close to his. The species appears also to be related to *Loxostomum abruptum* Phleger and Parker but never develops a terminal aperture. It particularly resembles the forms mentioned from the Gulf of Mexico, which were thicker and more twisted with more highly raised sutures (Phleger and Parker, 1951, p. 17, referred to *L. truncatum* Phleger and Parker (not Finlay, 1947)). It is possible that the study of larger suites of specimens from off the coast of California might show that Natland's species develops a terminal aperture also. This would probably necessitate the suppression of *L. abruptum* as a synonym. *B. minuta* is reported off the coast of California deeper than 274 m. It is found at low frequencies in Cores 248 and 252 associated with displaced faunal assemblages, and in Cores 233, 238, and surface samples 267, ATLANTIS Sta. 4,631, 4,633, and REHOBETH Sta. 3—38. The distribution is, therefore, in two distinct groups, one near the equator and the other between Latitudes 31° N and 37° N.

### **Bolivina paula** Cushman and Cahill

(Plate 7, figures 13, 14)

*Bolivina paula* Cushman and Cahill, 1932, in Cushman and Ponton, Bull. 9, Florida Geol. Surv., p. 84, pl. 12, figs. 6 a, b.

This species is described from the Miocene, Yorktown Formation, in Virginia and is reported from various Miocene localities of the eastern

United States. It is not reported from the Recent. The species is associated with displaced faunal assemblages in Cores 248, 252, and 267 off the equator and near St. Croix. It is probably of Recent origin and not present as a reworked fossil since no other reworked fossil forms have been found associated with the faunas with the possible exception of Core 267.

### **Bolivina petterssoni** Parker, n. sp.

(Plate 7, figures 15, 16, 17)

Test large, very gradually tapering, 2—3 times as long as broad, the widest part of the test being close to the apertural end, initial end rounded, periphery subacute at the initial end, rounded at the apertural end, the chambers of the early portion often overhanging, occasionally throughout most of the test in megalospheric forms; chambers inflated, with a maximum of 11 pairs, increasing gradually in height as added; sutures depressed, curving, at an angle of about 45° with the horizontal; wall translucent, with medium sized perforations uniformly scattered over the whole surface of the chambers; aperture broadly elliptical, slightly curved. Maximum length 0.83 mm.; width 0.33 mm.

Holotype from Core 221, ≠ 56, 549.5—550 cm. from the top, Lat. 22° 31′ N, Long. 23° 28′ W, at a depth of 4940 m.

This species differs from *B. malovensis* Heron-Allen and Earland in its larger size, more inflated chambers which overhang at the periphery at least in the early portion of the test, and broader aperture. It is found only in Core 221 where it occurs at frequencies varying from 1—50 % throughout most of the core.

### **Bolivina pseudoplicata**
Heron-Allen and Earland

(Plate 7, figures 18, 19)

*Bolivina pseudoplicata* Heron-Allen and Earland, 1930, Journ. Roy. Micr. Soc., vol. 50, p. 81, pl. 3, figs. 36—40.

In this species the character of the periphery varies greatly from rounded to sharply acute or even slightly keeled. Some of the specimen closely resemble those from Plymouth Sound This species is reported as a shallow wate form by most authors, from less than 90 m depth. Höglund, however, found that it wa most abundant at 200 m. in the Skagerak It is associated with displaced faunal assemblages in Cores 221, 228, 248, 252 and 267 It also occurs in Core 217 where there is sligh evidence of displacement of material. Al occurrences are south of Lat. 23° N.

### **Bolivina pseudopunctata** Höglund

(Plate 7, figures 20, 21)

*Bolivina pseudopunctata* Höglund, 1947, Zoo Bidrag från Uppsala, bd. 26, p. 273, pl. 2 fig. 5; pl. 32, figs. 23, 24; text. figs. 280 281, 287.

Höglund reports this species as most commo in the deeper parts of the Gullmar Fjord an the Skagerak. It has been observed off Gree land from 31—457 m. and at a few localiti in the Gulf of Maine. It is widely distribute in the cores, but only occurs in one surfa sample, SAN PABLO Sta. 3—47.

### **Bolivina pulchella** (d'Orbigny)

(Plate 7, figure 22)

*Sagrina pulchella* d'Orbigny, 1839, in de Sagra, Hist. Phys. Pol. Nat. Cuba, »Foramin fères», p. 150, pl. 1, figs. 23, 24.

This species is reported in the West India region, ranging from Rio de Janeiro to Be muda, from shallow depths to 1500 m. It found in Cores 248, 252 and 267 associat with displaced faunal assemblages.

### **Bolivina pusilla** Schwager

(Plate 7, figure 23)

*Bolivina pusilla* Schwager, 1866, Novara-Expe Geol. Theil., vol. 2, p. 254, pl. 7, fig. 101.

This species is reported from the Pacific between 154 m. and 2743 m. Specimens were compared with Pacific specimens in the Cushman collection at the U. S. National Museum and appear to be identical. It occurs in Core 290, near the bottom of the core, starting at 529.5 cm.

### **Bolivina subaenariensis** Cushman

(Plate 7, figures 24, 25)

*Bolivina subaenariensis* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 46, pl. 7, fig. 6.

This species is reported from the western North Atlantic, usually from depths greater than 114 m. Cushman (1937, p. 156) calls very similar specimens from the eastern Atlantic a variant form. Brady (1884, p. 423) reports this form as *B. aenariensis* (Costa) at depths greater than 155 m. Colom (1950, p. 22) reports *B. subaenariensis* off the coast of Africa at 312 m. The deepest reported occurrences are those of Brady at 2981 m. and Phleger (1942, p. 1081) at 1000 m. on the western Atlantic continental slope. The species is associated with displaced faunal assemblages in Cores 221, 248, 252, 258 and 262. It also occurs in the top sample of Core 280 and surface sample 228.

### **Bolivina tortuosa** H. B. Brady

(Plate 7, figure 26)

*Bolivina tortuosa* H. B. Brady, 1881, Quart. Journ. Micr. Soc., vol. 21, p. 57; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 420, pl. 52, figs. 31, 32 (not figs. 33, 34).

Most of the recorded occurrences of this species are from shallow water. Cushman (1937, p. 134) records it from the West Indian region from Brazil to Bermuda. Our occurrences, although probably displaced, fit this general pattern except for one occurrence in a core off the coast of Africa where Cushman's variety *atlantica* has been previously reported. The species is associated with displaced faunas in Cores 215, 248 and 252.

### **Bolivina** sp. 1

(Plate 7, figures 27, 28)

This species resembles *B. spathulata* (Williamson) but is less compressed, and has a less lobulate keel. The specimen figured on plate 27, figure 28, represents a broad form which may be the megalospheric form. There are too few specimens to study the species in detail and establish its identity. It is associated with a displaced faunal assemblage in Core 221.

### **Bolivina** sp. 2

(Plate 7, figure 29)

This species has apparently not been described. It is associated with fossil forms of possible Miocene age in Core 233. Only a few specimens were observed.

### **Uvigerina auberiana** d'Orbigny and variants

(Plate 7, figures 30, 31, 32, 33, 34, 35)

*Uvigerina auberiana* d'Orbigny, 1839, in de la Sagra, Hist. Phys. Pol. Nat. Cuba, »Foraminifères», p. 106, pl. 2, figs. 23, 24.

d'Orbigny figures a very small form, 0.33 mm. in length. Specimens of this size (Plate 7, figures 30—32) occur in Cores 288, 290 and in material from CHALLENGER Sta. 24 in the West Indies. In Core 267 south of St. Croix are specimens (plate 7, figures 34, 35) which are very much larger (1.5 mm. in length) but otherwise identical. Specimens of this type according to Cushman (1923, p. 163, pl. 42, figs. 3, 4) represent the typical form developed in the West Indies but this does not seem to be necessarily the case. Variant forms in both size groups are referable to *U. ampullacea* (Schwager) and appear to be well within the range of variation of *U.*

*auberiana*. For this reason it is probable that *U. ampullacea* should be placed in the synonymy under d'Orbigny's species. Many types of variation are seen in both size groups in shape of test and ratio of width to length. Often associated with the northern form in the cores are specimens (plate 7, figure 33) with slightly jutting chambers which are frequently spinose at the chamber margins. These specimens cannot be easily separated from the main group. The species occurs in Cores 215, 267, 288, 290 and at the surface at ATLANTIS Sta. 4631.

### **Uvigerina hollicki** Thalmann and variants

(Plate 8, figures 1, 2, 3)

*Uvigerina peregrina* Cushman var. *bradyana* Cushman, 1923 (not *U. bradyana* Fornasini), Bull. 104, U. S. Nat. Mus., pt. 4, p. 168, pl. 42, fig. 12.

*Uvigerina hollicki* Thalmann, 1950, Contr. Cushman Found. Foram. Res., vol. 1, pts. 3—4, p. 45.

Like most *Uvigerina* species *U. hollicki* is very variable. The variations are very much like those of the *U. peregrina* group but the costae are lower and the test often much larger in size. Variations occur in the degree to which the test is spinose. One variant form (plate 8, fig. 3) is very spinose and has more inflated chambers than usual. This form sometimes occurs with the more typical form and again may alternate with it at various depths in a core. It is listed as *U. hollicki* var. in the occurrence tables when it occurs alone, but is not differentiated when it occurs with the more typical form. Another variant form has a short, broad test (plate 8, figure 2). In Core 246 all specimens are of this type but they are difficult to differentiate when mixed with normal specimens. *U. hollicki* appears to replace in deep water *U. peregrina* which is found on the western continental slope. The species reported by Parker (1948) as *U. peregrina* var. *bradyana* is not referable to *U. hollicki*. *U. hollicki* is widespread in the cores and surface samples throughout the area.

### **Uvigerina senticosa** Cushman

(Plate 8, figures 4, 5)

*Uvigerina senticosa* Cushman, 1927, Bull. Scripps Instit. Ocean., Techn. Ser., vol. 1, no. 10, p. 159, pl. 3, fig. 14.

This species is not reported from the Atlantic but occurs off the coast of California at depths of less than 500 m. It is found in Core 221 associated with a displaced faunal assemblage.

### **Uvigerina** sp. 1

(Plate 8, figure 6)

This is a small costate form associated with displaced faunal assemblages in Cores 257 and 262.

### **Uvigerina** sp. 2

(Plate 8, figure 7)

This is a small, smooth form showing occasional traces of costae. It is associated with a displaced faunal assemblage in Core 257.

### **Rectuvigerina** sp.

(Plate 8, figure 8)

This species occurs only in Core 228 and has apparently never been described. It is somewhat compressed and has only one or two uniserial chambers. It is decorated with fine costae which are broken at the sutures. Mathews' (1945, p. 590) description of the genus *Rectuvigerina* does not include compressed forms but this species seems to conform to the description in every other way.

### **Angulogerina selseyensis** (Heron-Allen and Earland)

(Plate 8, figure 9)

*Uvigerina selseyensis* Heron-Allen and Earland, 1909, Journ. Roy. Micr. Soc., p. 437, pl. 18, figs. 1—3.

Core specimens are identical with Cuban specimens so identified by Bermudez (1935, p. 198). A topotype from Selsey, England, shore sands has a more elongate test but is similar in most respects. Additional specimens are needed to show the range of variation of the species and may reveal a specific difference between the western Atlantic and British forms. The species is reported as fossil from the Selsey shore sands and as Recent from shallow water off the north coast of Cuba. It is found in displaced faunal assemblages in Cores 248, 252, and 267 off St. Croix and the coast of Brazil.

## **Family ELLIPSOIDINIDAE**

### **Pleurostomella acuminata** Cushman

(Plate 8, figures 10, 11, 12, 13)

*Pleurostomella acuminata* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 50, pl. 19, fig. 6.

This species is reported from the Caribbean in deep water. It occurs in Cores 234, 242 and 267.

## **Family ROTALIIDAE**

### **Patellina corrugata** Williamson

(Plate 8, figure 14)

*Patellina corrugata* Williamson, 1858, Rec. Foram. Great Britain, p. 46, pl. 3, figs. 86—89.

This species is reported at all depths. It occurs in Cores 221, 223, 228, 246, 252, 267 and 292, but is not found in any of the surface samples.

### **Discorbis bertheloti** (d'Orbigny)

(Plate 8, figures 15 a, b)

*Rosalina bertheloti* d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, »Foraminifères», p. 135, pl. 1, figs. 28—30.

Hofker (1951, p. 359) has proposed the new genus *Discopulvinulina* with this species as the genotype. It appears, however, that this species is similar in its apertural characteristics to »*Rosalina globularis*» d'Orbigny, the genotype of the genus *Rosalina*. For this reason, if this species and other similar ones should be separated from the genus *Discorbis*, as seems probable, the generic name *Rosalina* should be used. We have not made this change here as it does not seem advisable until the situation is more thoroughly understood. *D. bertheloti* is reported from depths of 0—65 m. It is rare in Core 257 where it is associated with a displaced faunal assemblage.

### **Discorbis cf. columbiensis** Cushman

(Plate 8, figures 16, 17)

*Discorbis columbiensis* Cushman, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 43, pl. 6, figs. 13 a—c.

Very small specimens are found, not exceeding 0.25 mm. in diameter. The species is reported only from nearshore, shallow water. It occurs associated with displaced faunal assemblages in Cores 248, 252, and 267.

### **Discorbis mamilla** (Williamson)

(Plate 8, figures 18, 23, 24)

*Rotalina mamilla* Williamson, 1858, Rec. Foram. Great Britain, p. 54, pl. 4, figs. 109—111.

This species is placed in the genus *Discorbis* somewhat doubtfully. It has some characteristics in common with *Pninaella nitidula* (Chaster). The chief one is the presence of secondary plates covering the apertures of chambers previous to the final one, giving a star-shaped effect to the ventral side of the test. This characteristic was not described, however, by Brotzen (1948, p. 119) in his description of the genus *Pninaella.* The main feature of this genus is lacking in *D. mamilla:* the large size of the aperture such that the aperture occupies a large area of the septal wall as described by Brotzen and present in *Pninaella nitidula.* The aperture, however, is larger than in most species of *Discorbis.* This species has been frequently referred to *D. rosacea* (d'Orbigny). It is variable in height of spire, concavity of the ventral side, and acuteness of the periphery. Many of these variations are shown by Heron-Allen and Earland (1913, pl. 11, figs. 4—12) and referred by them to several species. *D. mamilla* is reported only from shallow water. It is associated with displaced faunal assemblages in Cores 215, 221 and 228.

### **Discorbis obtusa** (d'Orbigny)

(Plate 8, figures 25, 26, 27, 28)

*Rosalina obtusa* d'Orbigny, 1846, Foram. Foss. Bass. Tert. Vienne, p. 179, pl. 11, figs. 4 a—c.

Although this species is reported from the North Atlantic there is little data on its depth distribution. It is associated with displaced faunal assemblages in Cores 215 and 252.

### **Discorbis williamsoni** Parr

(Plate 8, figures 19, 20, 21, 22)

*Discorbis williamsoni* Parr, 1932, Proc. Roy. Soc. Victoria, vol. 44 (n. s.), pt. 2, p. 226, pl. 21, fig. 25.

*Rotalina nitida* Williamson (not. *R. nitida* Reuss, 1844), 1858, Rec. Foram. Great Britain, p. 54, pl. 4, figs. 106—108.

Included with this species are specimens (plate 8, figures 21, 22) referable to *D. parkerae* Natland (1950, p. 27). There is some doubt of the validity of this species as in most cases *D. williamsoni* is sufficiently variable to include low spired specimens with four or five chambers such as those that Natland describes. Specimens from the vicinity of the British Isles show such variations. Separation of the two forms could only be verified by statistical analysis and the species is not sufficiently common in the cores to carry out such an analysis. *D. williamsoni* is reported from 0—186 m. although most reports are from less than 100 m. *D. parkerae* is reported by Natland from less than 25 m. in the Gulf of California. The species is reported associated with displaced faunal assemblages in Cores 215, 221, 228, 248, 252 and 267. It also occurs in surface samples 246, ATLANTIS Sta. 4631, and SAN PABLO Sta. 3—47. A variant form questionably referred to this species occurs in Core 290.

### **Valvulineria araucana** (d'Orbigny)

(Plate 8, figures 29, 30)

*Rosalina araucana* d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, »Foraminifères», p. 44, pl. 6, figs. 16—18.

This species is reported in the Gulf of Mexico, chiefly between the depths of 80 m. and 160 m. It is associated with a displaced fauna in Core 252.

### **Valvulineria humilis** (H. B. Brady)

(Plate 8, figures 31, 32)

*Truncatulina humilis* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 665, pl. 94, figs. 7 a—c.

This species is reported deeper than 1830 m. in the Atlantic. It is so small that most specimens have probably occurred in the uncounted fine fractions. It is found in scattered cores throughout the area.

### **Gyroidina lamarckiana** (d'Orbigny)

(Plate 8, figures 33, 34)

*Rotalina lamarckiana* d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, »Foraminifères», p. 131, pl. 2, figs. 13—15.

This is a more compressed form than most species of *Gyroidina* but otherwise conforms most nearly to that genus. It resembles d'Orbigny's figures very closely in size and in other respects except for the character of the aperture which is not so extensive. It is a rather short opening about half-way between the umbilicus and the periphery, in some cases nearly reaching the periphery, with a definite lip. There are usually seven, occasionally eight, chambers in the last-formed whorl. The wall is thin, finely perforate, and slightly translucent. The only report is d'Orbigny's from the Canary Islands. It has a widespread occurrence in the cores and is found in surface samples 230, 232, 234, 257, 258, 261 and ATLANTIS Sta. 4637.

### **Gyroidina orbicularis** d'Orbigny

(Plate 8, figures 35, 36)

*Gyroidina orbicularis* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 278, no. 1; Modèles no. 13.

North Atlantic specimens are smaller than those from Rimini, Italy, but otherwise identical. The species is reported from deeper than 300 m. It is widespread in cores and surface samples.

### **Gyroidina soldanii** d'Orbigny variants

(Plate 9, figures 1, 2)

*Gyroidina soldanii* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 278, no. 5; Modèles no. 36.

North Atlantic specimens are apparently related to d'Orbigny's species but have fewer chambers, more slanting sutures than Rimini, Italy, specimens and usually a closed umbilicus. Frequently associated with them is a small species which is very difficult to separate from young specimens and which has been included with the counts of *G. soldanii.* Most records in the North Atlantic are from deeper than 500 m. although Parker (1948) records it from deeper than 90 m. on the western Atlantic continental shelf. It is widespread in the cores and surface samples.

### **Eponides polius** Phleger and Parker

(Plate 9, figures 3, 4)

*Eponides polius* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 21, pl. 11, figs, la, b, 2 a, b.

This species is reported in the northwestern Gulf of Mexico deeper than 1,000 m. It occurs in Cores 223, 235, 243, 246, 280 and surface samples 226 and 233.

### **Eponides pusillus** Parr

(Plate 9, figures 5, 6)

*Eponides pusillus* Parr, 1950, B. A. N. Z., Antarctic Res. Exped. 1929—1931, ser. B, vol. 5, pt. 6, p. 360, pl. 14, figs. 16 a—c.

This species seems identical with Parr's except that the adults usually have 6 chambers instead of 4 or 5 as he describes. The species is described, however, from only five Recent specimens which may not be truly representative of it. *E. pusillus* resembles *E. turgidus* Phleger and Parker but has a less convex dorsal side and more chambers, the latter having usually 4 in the last-formed whorl. It is recorded off Tasmania at three stations at 122—155 m. depth. Due to its small size many specimens occur in the uncounted fine fractions and therefore the occurrences listed in the tables probably do not appear as widespread in the Atlantic as they actually are. The species occurs in Cores 236, 242, 243, 246, 248, 252, 257, 258, 280 and 281.

### **Eponides tumidulus** (H. B. Brady)

(Plate 9, figures 7, 8)

*Truncatulina tumidula* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool. vol., 9, p. 666, pl. 95, figs. 8 a—d.

This species is reported from depths greater than 1,000 m. Like the previous species many specimens occur in the uncounted fine fractions. It is found in scattered cores and surface samples throughout the area.

### **Eponides umbonatus** (Reuss) and variants

(Plate 9, figures 9, 10)

*Rotalina umbonatus* Reuss, 1851, Zeitschr. deutsch. Geol. Ges., vol. 3, p. 75, pl. 5, figs. 35 a—c.

Specimens show a variation in the character of the periphery from subacute to rounded. Those with a rounded periphery are considered to be variants as topotypes have a uniformly subacute one. Other characteristics remain constant. The species is reported from deeper than 42 m. in the North Atlantic. It has a widespread occurrence in cores and surface samples.

### **Osangularia cultur** (Parker and Jones)

(Plate 9, figures 11, 16)

*Planorbulina cultur* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, p. 421, pl. 19, fig. 1.

This species is reported deeper than 920 m. in the North Atlantic and 600 m. in the Gulf of Mexico. It occurs in Cores 215, 221, 234, 238, 242, 246, 258, 267 and surface samples 224, 226, 267, ATLANTIS Sta. 4631 and 4633.

### **»Rotalia» beccarii** (Linné) variants

(Plate 9, figures 12, 13, 14, 15, 17, 18)

*Nautilus beccarii* Linné, 1758, Syst. Nat., ed. 10, p. 710.

No typical specimens of this species are found but several variant forms occur in small numbers. These include Shupack's variety *sobrina* (plate 9, figures 14, 15) and forms that have been often referred to »*Rosalina parkinsoniana*» d'Orbigny (plate 9, figures 17, 18). In Core 221 specimens are found with a thicker test than Rimini, Italy, specimens, and with a more papillate ventral side (plate 9, figures 12, 13). Variant forms occur associated with displaced faunal assemblages in Cores 221, 252, 257 and 258.

### **»Rotalia» praegeri**
### (Heron-Allen and Earland)

(Plate 9, figures 19, 20, 21)

*Discorbina praegeri* Heron-Allen and Earland, 1913, Proc. Roy. Irish Acad., vol. 31, pt. 64, p. 122, pl. 10, figs. 8—10.

Specimens found in Core 290 were compared with material from the vicinity of Ireland. The variation within the two groups differs in that the core specimens include some with 10 chambers in the last-formed whorl whereas the Irish ones have a maximum of 7. In both cases the size of the ventral plugs varies greatly. The species is reported from the vicinity of the British Isles. Reports from other areas are not accompanied by figures and as this species may be confused very easily with »*R.*» *translucens* Phleger and Parker they are not included here.

### **»Rotalia» translucens** Phleger and Parker

(Plate 9, figures 22, 23)

*Rotalia translucens* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 24, pl. 12, figs. 11 a, b, 12 a, b.

This species varies from the previous one in being in mos tcases plano-convex, the dorsal side being flat, or very slightly convex. »*R*». *praegeri* has a convex dorsal side and flat or concave ventral side. *R. translucens* seldom has more than 5 chambers in the last-formed whorl. It is reported from the northwestern Gulf of Mexico from 25—1,000 m. It is associated with displaced faunal assemblages in Cores 228 and 252.

### **Höglundina elegans** (d'Orbigny)

(Plate 9, figures 24, 25)

*Rotalia* (*Turbinulina*) *elegans* d'Orbigny, 1826, Ann. Sci. Nat. vol. 7, p. 276, no. 54 (not *R. elegans* d'Orbigny, ibid., p. 272, no. 6). — Jones and Parker, 1860, Quart. Journ. Geol. Soc., vol 16, pl. 20, fig. 46.

This species is reported in the North Atlantic deeper than 42 m. It occurs in scattered cores and surface samples throughout the area.

### **Cancris cf. oblonga** (Williamson)

(Plate 9, figures 26, 27)

*Rotalina oblonga* Williamson, 1858, Rec. Foram. Great Britain, p. 51, pl. 4, figs 98—100.

The few specimens which occur are small and cannot be identified with certainty. The maximum reported depth for *C. oblonga* in the North Atlantic is 200 m. The specimens are associated with displaced faunal assemblages in Cores 221 and 228.

## Family AMPHISTEGINIDAE

### **Amphistegina lessonii** d'Orbigny

(Plate 9, figures 28, 29)

*Amphistegina lessonii* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 304, no. 3, pl. 17, figs. 1—4; Modèle, no. 98.

Juvenile specimens occur in displaced faunal assemblages in Cores 215, 248, 252 and 267. Most previous records for the species are from 0—90 m. depth in mid-latitudes.

## Family CYMBALOPORIDAE

### **Tretomphalus atlanticus** Cushman

(Plate 9, figures 30, 31)

*Tretomphalus atlanticus* Cushman, 1934, Contr. Cushman Lab. Foram. Res., vol. 10, pt. 4, p. 86, pl. 11, figs. 3 a—c; pl. 12, fig. 7.

Most reported occurrences are from the West Indian region in shallow water. No planktonic stages of this species occur in our material. Benthonic forms occur in Cores 228, 267 and surface sample 267.

## Family CASSIDULINIDAE

### **Epistominella exigua** (H. B. Brady)

(Plate 9, figures 35, 36)

*Pulvinulina exigua* H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 696, pl. 103, figs. 13, 14.

This species is reported deeper than 117 m., with most records deeper than 275 m. It has a widespread occurrence in the cores and surface samples.

### **Epistominella (?) umbonifera** (Cushman)

(Plate 9, figures 33, 34)

*Truncatulina pygmaea* H. B. Brady (not Hantken, 1875), 1884, Rep't. Voy. CHALLENGER, Zool. vol. 9, p. 666, pl. 95, figs. 9 a—c, 10.

*Pulvinulinella umbonifera* Cushman, 1933, Contr. Cushman Lab. Foram. Res., vol. 9, pt. 4, p. 90, pl. 9, figs. 9 a—c.

? *Eponides bradyi* Earland, 1934, DISCOVERY Rep'ts., no. 10, p. 187, pl. 8, figs. 36—38.

*Pulvinulinella* sp. A, Cushman and Henbest, 1940, U. S. Geol. Surv. Prof. Paper 196—A, p. 36, pl. 10, fig. 5.

Cushman's holotype of this species is a very poor, small specimen but is identical with small specimens of the species in our material. Additional specimens from the same general locality from which Cushman described his species are large, well-developed forms, also identical with ours. The species attains a maximum diameter of 0.6 mm. Cushman describes it as having a maximum of 6 chambers in the adult whorl but there may be as many as 9. The sutures often appear as white lines if the test is sufficiently transparent to reveal a part of the septa; in other specimens they appear as dark, narrow lines.

This species is retained in the genus *Epistominella* with considerable doubt. In many respects it most closely resembles the genus *Nuttallides* Finlay especially as regards the nature of the aperture, which starts near the umbilical region and turns into the plane of coiling near the periphery, extending only a short distance into the chamber. In some specimens the aperture is much closer to the *Eponides* — type aperture. This is in line with Earland's statement in his description of *Eponides bradyi* that Brady's »*Truncatulina pygmaea* Hantken» should be placed in the genus *Eponides*. Brady's figured specimens appear to be identical with ours although the nature of the aperture cannot be seen very clearly. Earland's species *Eponides bradyi* is placed in the synonymy tentatively as his types could not be checked. Cushman's (1927, p. 165, pl. 5, figs. 11—13) species *Epistominella bradyana* in whose synonymy he places Brady's »*Truncatulina pygmaea*» appears from the figures to be a different form with a finely perforate wall and a true *Epistominella* type of aperture. The types of this species have not been studied. *E. umbonifera* is reported from the Atlantic in deep water. It has a widespread occurrence in cores and surface samples.

### **Cassidulina carinata** A. Silvestri

(Plate 9, figures 32, 37)

*Cassidulina laevigata* d'Orbigny var. *carinata* A. Silvestri, 1896, Accad. Pont. Nuovi Lincei, Mem. 12, p. 104, pl. 2, fig. 10 (*C. laevigata* in explanation of plate).

Our specimens are similar to ones from the Pliocene of Siena, Italy. The species named *C. laevigata* var. *carinata* by Cushman (1922, p. 124) and later changed to *C. neocarinata* by Thalmann (1950, p. 44) is different and apparently not so widely distributed. Cushman's species has a long, narrow apertural face and slit-like aperture with a narrow tooth. *C. carinata* has a broader apertural face and tooth, is less compressed and is more coarsely perforate. Many of the forms which have been referred to Cushman's form should be referred to Silvestri's. Neither species shows much resemblance to *C. laevigata* which has a more rounded apertural face and very small aperture, set at an angle and without the plate-like tooth. The records of these various species are so confused that it is impossible to give the distribution accurately. Brady's (1884, pl. 54, fig. 3) figure of »*C. laevigata*» from west of Ireland is undoubtedly *C. carinata*. It has also been observed in Mediterranean and Arctic material. Specimens of *C. neocarinata* occur on the western Atlantic continental shelf and the species is common in the Gulf of Mexico at depths of less than 1,000 m. It is not found in the deep sea cores and is perhaps confined to shallower depths in the Atlantic as it was in the Gulf of Mexico (Phleger, 1951, p. 45. — listed as *C. laevigata* var. *carinata*). *C. carinata* is widely distributed in the southern cores and occurs in Cores 288, 289, 292, 293 and 296 in the northern area. It also occurs in surface samples 224 and SAN PABLO Sta. 3—47.

### **Cassidulina crassa** d'Orbigny

(Plate 10, figure 1)

*Cassidulina crassa* d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, »Foraminifères», p. 56, pl. 7, figs. 18—20. — H. B. Brady, 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 429, pl. 54, fig. 5.

Included in the counts of this species in some of the northern group of cores are specimens of *C. islandica* Nørvang. The latter species is less compressed than *C. crassa* and has a thin plate-like tooth partially concealing the aperture. *C. crassa* is reported from 73—4300 m. in the North Atlantic and at similar depths in the Gulf of Mexico. *C. islandica* is reported off Iceland at 38—220 m. *C. crassa* occurs in scattered cores throughout the area but never in abundance. It is found in only three surface samples: ATLANTIS Sta. 4631, SAN PABLO Sta. 3—47 and REHOBETH Sta. 3—32.

### **Cassidulina curvata** Phleger and Parker

(Plate 10, figure 2)

*Cassidulina curvata* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 26, pl. 14, figs. 5 a, b.

This species is easily confused with *C. laevigata.* One important difference between the two, not mentioned in the original description, is in the apertural characteristics. The aperture of C. *curvata* is in the plane of coiling with no protruding apertural face visible from the side. *C. laevigata* has a rounded apertural face into which the aperture projects at an angle. *C. curvata* is reported as *C.* sp. (Parker, 1948, p. 237) deeper than 90 m. on the western Atlantic continental shelf. It is associated with a displaced faunal assemblage in Core 252.

### **Cassidulina norcrossi australis**
### Phleger and Parker

(Plate 10, figure 3)

*Cassidulina norcrossi australis* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 27, pl. 14, figs. 8 a, b, 9, 10.

This species is reported from 200—700 m. in the northwestern Gulf of Mexico. A few specimens are found associated with displaced faunal assemblages in Cores 252 and 257.

### **Cassidulina reflexa** Galloway and Wissler

(Plate 10, figures 6, 7)

*Cassidulina reflexa* Galloway and Wissler, 1927, Journ. Pal., vol. 1, no. 1, p. 80, pl. 12, fig. 13.

The North Atlantic species is very similar to Galloway and Wissler's, described from the Pleistocene of California, although a few very large specimens measuring over 1.00 mm. in length are found. The holotype, not seen, is 0.32 mm. in length and most of the specimens found are comparable in size. *C. reflexa* is reported from the Middle Miocene of Haiti by Coryell and Rivero (1940, p. 342). Specimens from the Miocene of Haiti collected by W. P. Woodring are identical with our specimens. The species is found in the lower part of Cores 233 and 238.

### **Cassidulina subglobosa** H. B. Brady

(Plate 10, figure 4)

*Cassidulina subglobosa* H. B. Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 30 (60); 1884, Rep't. Voy CHALLENGER, Zool., vol. 9, p. 430, pl. 54, figs. 17 a—c.

This species is very variable in size and may be more properly defined as a »species group». It is reported from depths of 37—1610 m., usually deeper than 185 m. It is widely distributed throughout the cores and surface samples.

### **Cassidulina** sp. 1

(Plate 10, figure 5)

This species resembles *G. subglobosa* but is somewhat compressed, with less-inflated chambers. It is more common in the Mediterranean than the North Atlantic where it is found associated with a displaced faunal assemblage in Core 215.

### **Cassidulina** sp. 2

(Plate 10, figures 8, 9)

This species has not been previously described. It resembles *C. palmerae* Bermudez and Acosta in its reticulate ornamentation but differs in the character of the aperture which lies in the plane of coiling, in the acuteness of the periphery at the apex of the test, and in other respects. It most closely resembles *C. favus* (H. B. Brady) but is more highly convex. A few specimens are found in Cores 233 and 238, in the former associated with the presumed Miocene assemblage.

### **Cassidulinoides mexicana** (Cushman)

(Plate 10, figures 10, 11)

*Cassidulina mexicana* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 131, pl. 24, fig. 5.

This species is reported from a depth of 40 m. off the coast of Florida and from 1488 m. in the Caribbean Sea. The holotype is identical with our smaller specimens. Cushman described the species from only two specimens and was therefore ignorant of the range of variation of the form. Specimens from Core 221, sample 56, range in length from 0.29—0.86 mm. Specimens are found associated with displaced faunal assemblages in Cores 221 and 248.

### **Ehrenbergina trigona** Goës

(Plate 10, figures 12 a, b, 13)

*Ehrenbergina serrata* Reuss var. *trigona* Goës, 1896, Bull. Mus. Comp. Zool., vol. 29, no. 1, p. 49.

*Textularia triquetra* Goës (not von Münster, 1838), 1882, Kongl. Svensk. Vet. Akad. Handl., vol. 19, no. 4, p. 83, pl. 6, figs. 183, 184.

*Ehrenbergina serrata* H. B. Brady (not Reuss, 1850), 1884, Rep't. Voy. CHALLANGER, Zool., vol. 9, p. 434, pl. 55, figs. 2, 3, (not 4—7).

*Ehrenbergina bradyi* Cushman, 1922, Bull. 104, U. S. Nat. Mus., pt. 3, p. 134, pl. 26, fig. 5; 1927, Proc. U. S. Nat. Mus., vol. 70, art 16, p. 5, pl. 2, figs. 1 a—c.

There has been much confusion between this species and the one following (*E. undulata* Parker, n. sp.). Goës placed Brady's figures of *E. serrata* in the CHALLENGER Report in the synonymy under his species, but included all of them. He placed his own reference to *Textularie triquetra* of 1882 after Brady's. His figured specimen clearly refers to the same species figured by Brady (pl. 55, figs. 2, 3). In 1922 Cushman described *E. bradyi* whose holotype, seen at the U. S. National Museum in Washington, D. C., is definitely referable to Goës' species. Cushman later confirmed this in 1927 by placing Brady's pl. 55, figs. 2, 3, 5(?) only in the synonymy under his species *E. bradyi*, although in 1922 he placed Brady's pl. 55, figs. 6, 7 only in the synonymy. Many later authors have called this species *E. bradyi*. *E. trigona* is characterized by its trigonal shape, the rather broadly divided central furrow whose sharp boundaries terminate in spines at each chamber, and the concave sides and concave to flat dorsal side. Goës reports the species from deeper than 549 m. The form referred by Colom (1950, p. 28) to *E. bradyi* is probably *E. trigona* and is reported in his facies from 150—475 m. off the coast of Africa. E. *trigona* occurs in Cores 238, 242 and 279.

### **Ehrenbergina undulata** Parker, n. sp.

(Plate 10, figures 14, 15 a, b, 16)

*Ehrenbergina trigona* Cushman 1922 (not Goës, 1896), Bull. 104, U. S. Nat. Mus., pt. 3, p. 135, pl. 26, fig. 4; 1927, Proc. U. S. Nat. Mus., vol. 70, art. 16, p. 6, pl. 2, fig. 3; 1936, Bull. Geol. Soc. America, vol. 47, p. 425, pl. 3, figs. 9 a, b.

Test large, triangular in cross-section in early portion of test, later compressed, the early portion on the ventral side with a very narrow central furrow formed from the carinated margins of the chambers, sometimes merging into a single keel, with occasionally on some specimens a projecting spine, young forms sometimes showing the keels throughout the test, the sides of test carinate with a heavy spine at each chamber; chambers non-inflated in early portion, later slightly inflated; sutures limbate, flush with surface in early portion, later slightly depressed; wall smooth except or a few spines and occasional tubercles on the nitial portion of test and the occasional spines n the central furrow and the marginal spines, inely perforate; aperture normal. Maximum ength 0.83 mm.; maximum width 0.75 mm.

The holotype is from Core 290, ≠ 21 (219.5—220 cm. from top), Lat. 41° 35′ N., Long. 29° 37′ W at a depth of 1995 m.

This species varies in the amount of the test showing a sharply triangular cross-section. It differs from *E. trigona* in not having the deep, rather broad central furrow on the ventral side decorated with a spine at each chamber, in the less deeply concave areas on each side of the central portion of the ventral side, in the somewhat convex dorsal side, non-trigonal ater portion of the test, and in having the initial portion of the test decorated with spines. Cushman reports it from depths greater than 33 m. The figured specimens of all the references given in the synonymy have been studied. The specimens referred to *E. serrata* Reuss by Cushman and Henbest (1940, pl. 10, fig. 10) from North Atlantic deep-sea cores are also eferable to *E. undulata*. *E. undulata* is widely distributed in the cores, except for those off the coast of Brazil, and is found in surface sample ATLANTIS Sta. 4631.

## Family CHILOSTOMELLIDAE

### Rotamorphina laevigata (Phleger and Parker)

(Plate 10, figures 17, 23)

*Valvulineria laevigata* Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 25, pl. 13, figs. 11 a, b, 12 a, b.

This species is referred to the wrong genus by Phleger and Parker. There are usually 5 chambers, occasionally 4 or 6, in the adult whorl. The distinction between Finlay's genera *Quadrimorphina* and *Rotamorphina* seems a rather arbitrary one. Future investigation may ead to a combination of the two. *R. laevigata* s reported deeper than 300 m. in the North Atlantic by Parker (1948, p. 225) as *Valvulineria* sp. and by Cushman (1931, p. 44) as *Eponides exigua* (H. B. Brady) (not *Pulvinulina exigua* H. B. Brady). It occurs in Cores 221, 248 and surface samples 224, 225 and 228.

### **Chilostomella oolina** Schwager

(Plate 10, figure 18)

*Chilostomella oolina* Schwager, 1878, Boll. Com. Geol. Ital., vol. 9, p. 527, pl. 1, fig. 16.

This species is reported in most cases deeper than 200 m. although there are a few shallow occurrences. It is widely distributed in the cores but is not found in the surface samples.

### **Pullenia bulloides** (d'Orbigny)

(Plate 10, figure 19)

*Nonionina bulloides* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 293, no. 2; 1846, Foram. Foss. Bass. Tert. Vienne, p. 107, pl. 5, figs. 9, 10.

Young specimens of this species are frequently assymetrical. This feature does not appear in adults. The species is widely reported, and has a widespread occurrence in the cores and surface samples.

### **Pullenia quinqueloba** (Reuss)

(Plate 10, figure 20)

*Nonionina quinqueloba* Reuss, 1851, Zeitschr. deutsch. Geol. Ges., vol. 3, p. 71, pl. 5, fig. 31.

This species is reported deeper than 80 m. but is found most commonly deeper than 940 m. It has a widespread occurrence in cores and surface samples.

### **Pullenia** cf. **riveroi** Bermudez

(Plate 10, figure 21)

*Pullenia riveroi* Bermudez, 1939, Mem. Soc. Cubana Hist. Nat., vol. 13, no. 1, p. 11, pl. 2, figs. 1—6.

North Atlantic specimens are referred tentatively to this species. They appear to be identical with Bermudez' figure 4 in the above reference. None of the specimens resemble his other figured types. Bermudez says that figure 4 represents a juvenile specimen. Adult specimens are very broad in apertural view, and inflated. He reports the species off Cuba deeper than 1,042 m. It occurs in Cores 252 and 267 associated with displaced faunal assemblages, and in surface sample 267.

### **Pullenia** sp.

(Plate 10, figure 22)

This species occurs only in small numbers. It is more compressed than the previous species, with a lobulate periphery and 6—7 chambers in the adult whorl. It somewhat resembles *P. salisburyi* R. E. Stewart and K. C. Stewart but has a more rounded periphery. It is apparently a new species but insufficient specimens occur in any one sample to adequately describe it. *Pullenia* sp. has a widespread occurrence in cores and is found in surface samples 257, 258, 261, 267, 280, 284, 285, ATLANTIS Sta. 4637, 4739, 4742, and in REHOBETH Sta. 3—29.

## Family ANOMALINIDAE

### **Anomalina balthica** (Schroeter)

(Plate 10, figures 24, 25)

*Nautilus balthicus*, 1783, Einleitung Conch. Kenntn. vol. 1, p. 20, pl. 1, fig. 2.

*Nonionina elegans* Williamson (not *Anomalina elegans* d'Orbigny, 1826), 1858, Recent Foram. Great Britain, p. 35, pl. 3, figs. 74, 75.

This identification has been generally accepted by authors since Cushman (1931, p. 108) revived it. It is somewhat questionable owing to the great discrepancy in the number of chambers in the last-formed whorl of the form figured by Schroeter and the forms later referred to it. Schroeter's figure shows 24 chambers in the last-formed whorl, while an examination of numerous specimens from various localities gives a maximum of 1 The species is recorded from numerous localiti near the British Isles and elsewhere in th eastern Atlantic to a depth of 2,981 m. Colo (1950) records it as frequent to abundant in h deepest facies, 300—878 m., off the west coa of Africa. It is associated with displace faunal assemblages in Cores 221 and 228 o Africa and the Cape Verde Islands.

### **Anomalina** sp.

(Plate 10, figures 26, 27, 28)

This species resembles Brady's figures in th CHALLENGER Report (Brady, 1884, pl. 9 figs. 4, 5) of »*Anomalina grosserugosa*», bu appears to be more finely perforate on th involute side. Brady's species is not the sam as Gümbel's and is probably a new species a pointed out by Thalmann (1933, p. 254). study of Brady's material might reveal tha our species is the same as his. It has the following characteristics: a broadly rounded periphery, six chambers in the last-formed whor a coarsely perforate evolute side and smoot more finely perforate involute side, a maximu diameter of 0.6 mm. The species occurs in ver small numbers in many of the cores througho the area, but there is insufficient material t fully reveal its characteristics and variation.

### **Planulina ariminensis** d'Orbigny

(Plate 11, figures 3, 4)

*Planulina ariminensis* d'Orbigny, 1826, Ann Sci. Nat., vol. 7, p. 280, no. 1, pl. 14, fig 1—3.

Most of the specimens are small. The resemble Rimini specimens although the pun tae are not well defined due to poor preservation. *P. ariminensis* is reported deeper tha 275 m., but is found in shore sands at Rimin Italy. It occurs in Cores 215 and 290.

### **Planulina wuellerstorfi** (Schwager)

(Plate 11, figures 1, 2)

*Anomalina wuellerstorfi* Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 258, pl. 7, figs. 105, 107.

This species is very variable in North Atlantic material. The greatest variation is in the amount of compression of the test, some of the specimens being very convex on the involute side. These convex forms are probably referable to *P. bradyi* Tolmachoff but have not been differentiated as such in our material. The species lies in the transition zone between the genera *Planulina* and *Cibicides*. It is reported in the Atlantic deeper than 630 m. and has a widespread occurrence in the cores and surface samples.

### **Laticarinina pauperata** (Parker and Jones)

(Plate 11, figure 5, 6)

*Pulvinulina repanda* var. *menardii* subvar. *pauperata* Parker and Jones, 1865, Phil. Trans. Roy. Soc. London, vol. 155, p. 395, pl. 16, figs. 50, 51 a, b.

This species is reported deeper than 200 m. It is found at low frequencies in scattered cores and surface samples throughout the area.

### **Cibicides kullenbergi** Parker, n. sp.

(Plate 11, figures 7, 8)

Test large, biconvex, the evolute side much less convex than the involute, composed of three whorls, periphery acute with a narrow keel, regular; chambers distinct, 11—13 in the last-formed whorl, meeting at the center on the involute side in an area of clear shell material of varying size which does not protrude to form a raised umbo; sutures flush with the surface on both sides, curved; wall thick, partially translucent depending on the state of preservation of the specimens, finely perforate on the involute side, with a few large punctae rather widely spaced on each chamber on the evolute side; aperture peripheral, extending into the evolute side. Maximum diameter 0.8 mm.; thickness 0.43 mm.

The holotype is from REHOBETH Sta. 3—38, Lat. 36° 34′ N, Long. 38° 15′ W, at a depth of 3109 m.

This species differs from *C. robertsonianus* (H. B. Brady) in the less translucent wall, fewer chambers in the adult form, broader and fewer whorls, more curving sutures on the evolute side and the more widely spaced, large punctae on the evolute side. It differs from *C. mundula* (Brady, Parker and Jones) in its much larger size, the greater convexity of the involute side and in the aperture which extends onto the evolute side even in young specimens. It is common in many of the cores, mostly in the northern group, and is widespread in the surface samples. It appears to be a true deep-sea form.

### **Cibicides lobatulus** (Walker and Jacob)

(Plate 11, figures 9, 14)

*Nautilus lobatulus* Walker and Jacob, 1798, Adams Essays, Kannmacher's ed., p. 642, pl. 14, fig. 36.

This species is widely reported in the North Atlantic. It is in many cases associated with displaced faunal assemblages in the cores. It occurs in Cores 215, 221, 228, 233, 235, 252 and 257.

### **Cibicides** cf. **refulgens** Montfort

(Plate 11, figures 10, 11)

*Cibicides refulgens* Montfort, 1808, Conch. Syst., vol. 1, p. 123. »Hammonia *Balanus* seu *Balanoidea*», Soldanii, 1789, Test., vol. 1, pt. 1, p. 58, pl. 46, figs. *nn*, *oo*.

North Atlantic specimens resemble those from Rimini except for their smaller size (maximum diameter 0.47 mm.). Brady (1884,

p. 659) reports the species between. N. Lats. 47° and 62° at depths from 82—4390 m. Specimens occur associated with displaced faunal assemblages in Cores 215, 248, 252, 257, and 267 south of this area.

### **Cibicides robertsonianus** (H. B. Brady)

(Plate 11, figures 15, 16, 17)

*Truncatulina robertsoniana* H. B. Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 65; 1884, Rep't. Voy. CHALLENGER, Zool., vol. 9, p. 664, pl. 95, figs. 4 a—c.

Records for this species in the North Atlantic are from depths greater than 700 m. In the Gulf of Mexico it is recorded deeper than 450 m. It is widespread in the cores and surface samples.

### **Cibicides** sp.

(Plate 11, figures 18, 22)

This species is more compressed than *C. lobatulus*, non-lobulate in the earlier part of the keeled test but with the last-formed chambers irregular and flaring. The sutures are limbate. The species occurs in small numbers in cores and surface samples throughout the area.

### **Cibicidina rhodiensis** (Terquem)

(Plate 11, figures 12, 13)

*Truncatulina rhodiensis* Terquem, 1878, Mém. Soc. Géol. France, ser. 3, vol. 1, pt. 3, p. 21, pl. 1 (6), figs 26 a—c.

North Atlantic specimens are identical with ones from the Mediterranean. Said (1949, p. 42) in comparing this species with *C. americanus* (Cushman) states that it differs in having a narrow keel. He has obviously referred to the »*Truncatulina americana*» described by Cushman (1918 a, p. 63, pl. 20, figs. 2, 3; pl. 21, fig. 1) from the Miocene of the Atlantic Coastal Plain. The holotype of this species has the catalogue no. U. S. N. M. 325328. In the same year Cushman (1918, p. 68, pl. 23, figs. 2 a—c) named a species »*Truncatulina americana*» from the Culebra Formation of Panama, whose holotype has the catalogue no. U. S. N. M. 324665. On the basis of this earlier number it seems reasonable to give priority to the Panama species. It is a keeled form very similar to Terquem's. Said records *C. rhodiensis* in the Red Sea from 30—512 m. It is found associated with displaced faunal assemblages in Cores 221 and 252.

## **Family PLANORBULINIDAE**

### **Planorbulina mediterranensis** d'Orbigny

(Plate 11, figures 20, 21)

*Planorbulina mediterranensis* d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 2, pl. 14, figs. 4—6 bis; Modèles, no. 79.

This species is reported to a depth of 1160 m., but is more common at less than 150 m. It occurs in Cores 215, 221 and 228 associated with displaced faunal assemblages.

## **Family RUPERTIIDAE**

### **Rupertia stabilis** Wallich

(Plate 11, figure 19)

*Rupertia stabilis* Wallich, 1877, Ann. Mag. Nat. Hist., ser. 4, vol. 19, p. 502, pl. 20, figs. 1—13.

This species is reported from scattered stations in various parts of the North Atlantic from 9—2515 m. It occurs in Cores 233, 267 and 290.

## Planktonic Foraminifera in Surface Sediment Samples

### *Distribution*

The populations of planktonic Foraminifera were analyzed in 53 samples of surface sediment rather generally distributed in this area of the Atlantic. These samples were obtained with the short coring tube described by Phleger (1951, p. 3) and it is assumed that the faunas epresent the modern accumulation of tests. The samples taken are 1 cm. in thickness, and lthough the material at the surface may be onsidered to accurately represent modern naterials, the lower part of each sample was leposited at some time in the past.

A problem in the use of bottom samples is hat the planktonic fauna occurring in the ediment did not necessarily live in the water lirectly above the position of any sample. Planktonic Foraminifera are transported by he water masses which they inhabit, and hey may be transported during life or after leath. A population from a sediment may ave been transported a considerable distance efore deposition. Also, a population may be ntroduced by a water mass representing a oreign environment, the specimens killed, and leposited. Ecological interpretations from sediment samples may be misleading unless the listribution and movements of water masses re taken into account. All these qualifications hould be considered in interpreting data on listribution of planktonic Foraminifera from ediments.

The most realistic distribution method of study f the ecology of planktonic Foraminifera is rom plankton tows collected from all depths of vater. This is a laborious procedure, both in he field and in the laboratory, and has not een possible in this study. The use of faunas rom bottom samples is the best approximation vhich can be made at the present time.

The distributions of the principal planktonic pecies are plotted on Figures 3—19. Total opulations are plotted on Figure 20 for those amples which were equal in size. Some of he samples furnished were of different sizes nd are not included in any population counts. he distribution of each planktonic species n these bottom samples is discussed below. he generalizations about distributions apply nly to the occurrences in the present suite of amples, unless otherwise specified. The samples with low total populations (see Figure 20) are generally disregarded in the following discussions.

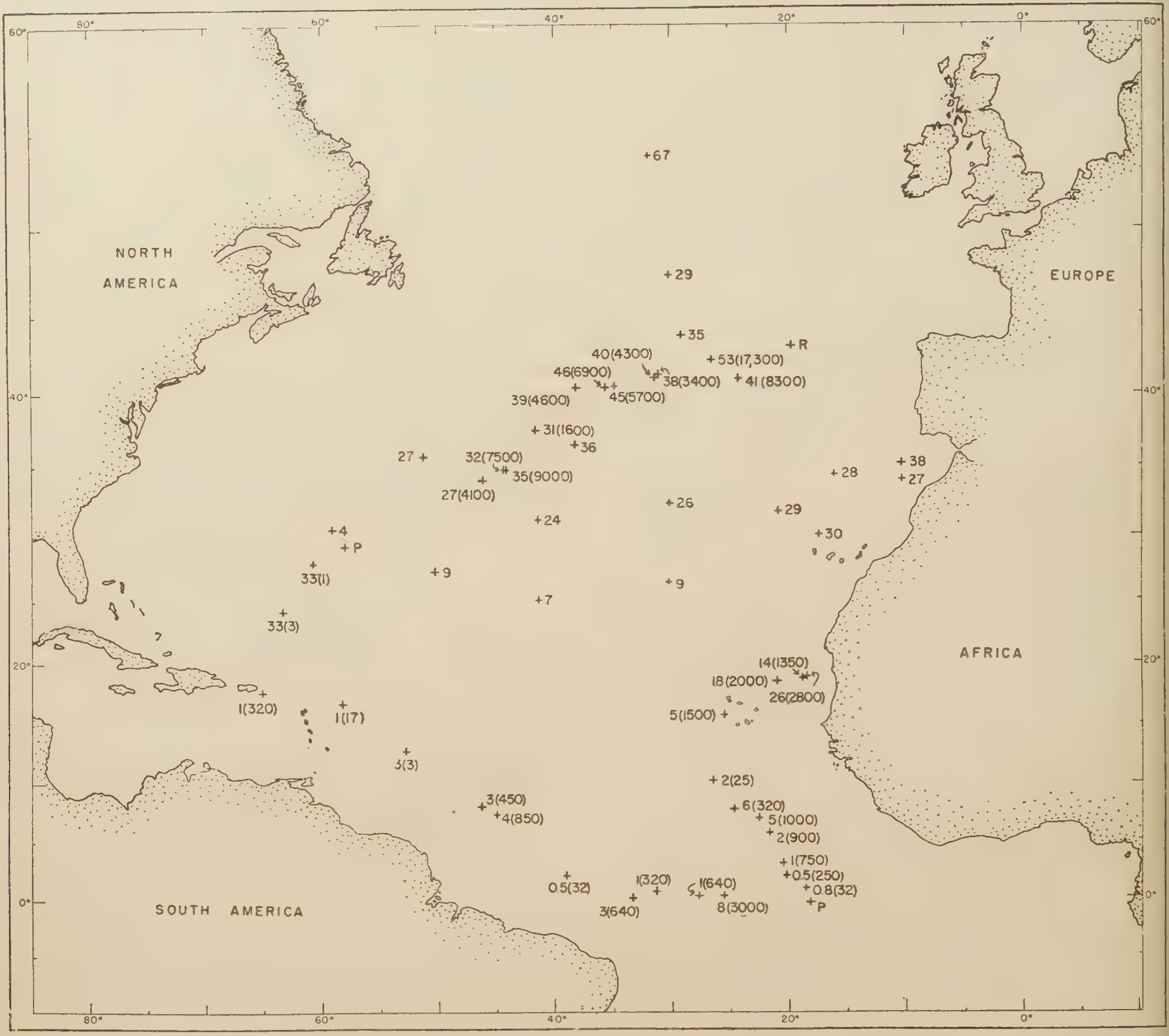
*Globigerina bulloides* is recorded from all stations but the frequencies have significant differences. It is most abundant north of approximately 30° N Lat., where the frequencies range from 24 % to 67 % of total population with an average frequency of 30—40 %. South of 30° N Lat. the significant frequencies are less than 10 % except at three stations near the west coast of Africa, between Cape Verde and Cape Blanco, where frequencies are 14—26 %. Frequencies are generally 5 % or less south of approximately 15° N. Lat. The frequency boundary at about 30° N. appears to be rather pronounced, but this may be an effect of the spacing of the samples over such a wide area.

*Globigerina eggeri* is recorded from all but six stations. The highest frequencies occur south of 20° N. Lat. where it may be more than 25 % of the population. In the equatorial mid and western Atlantic the frequencies are somewhat lower. Significant percentages occur at the mid-Atlantic stations between approximately 35° N. Lat. and 42° N. Lat.

*Globigerina inflata* seems to be a mid-latitude species, being essentially restricted to north of 15° N. Lat. The highest frequencies occur at three stations off west Africa between Cape Verde and Cape Blanco where they are 30—34 %. Elsewhere north of the Fifteenth Parallel it ranges between about 10—20 % at the majority of stations. This species is recorded at very low frequencies from only two of the present stations south of 15° N. Lat.

*Globigerina pachyderma* has a distinctly northern distribution, being essentially restricted to north of 35° N. Lat. and with no record south of about 27° N. Lat. Frequencies are generally low, but there is an apparent increase at about 45° N. Lat.

*Globigerinella aequilateralis* is universally distributed at most stations, except the two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+41(8300)
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+36
27 +
32(7500)
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+7
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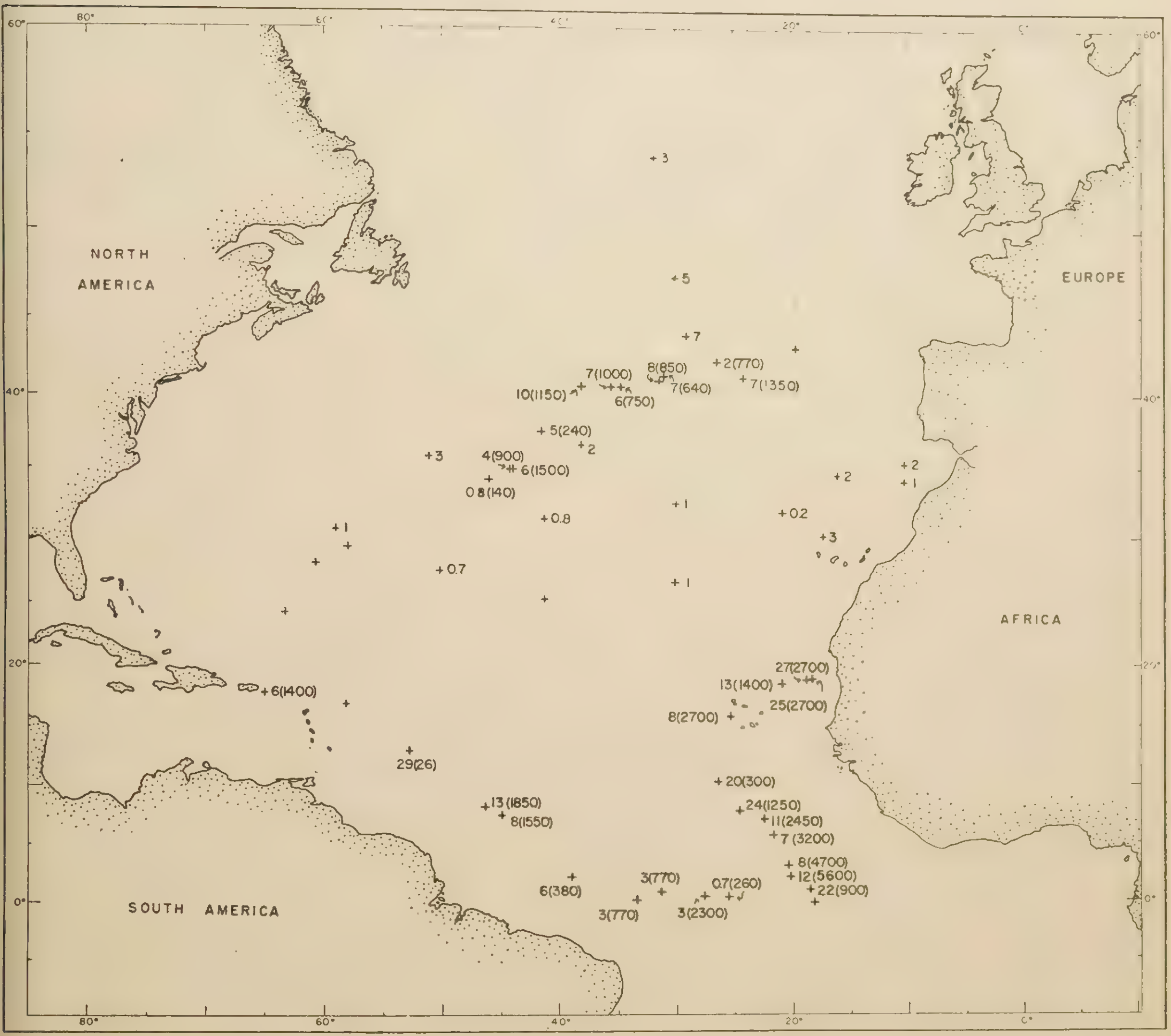
18(2000) +
26(2800)
1(320)
1(17)
5(1500) +
3(3)
+2(25)
3(450)
4(850)
+6(320)
5(1000)
2(900)
+1(750)
+0.5(250)
0.5(32)
1(320)
1(640)
0.8(32)
3(640)
8(3000)
P

Fig. 3. Distribution of *Globigerina bulloides* d'Orbigny in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera second number, in parentheses, is estimated actual number of specimens.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+2(770)
7(1000)
10(1150)
6(750)
7(640)
7(1350)
+5(240)
+2
+3
4(900)
6(1500)
0.8(140)
+2
+2
+1
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+0.8
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+3
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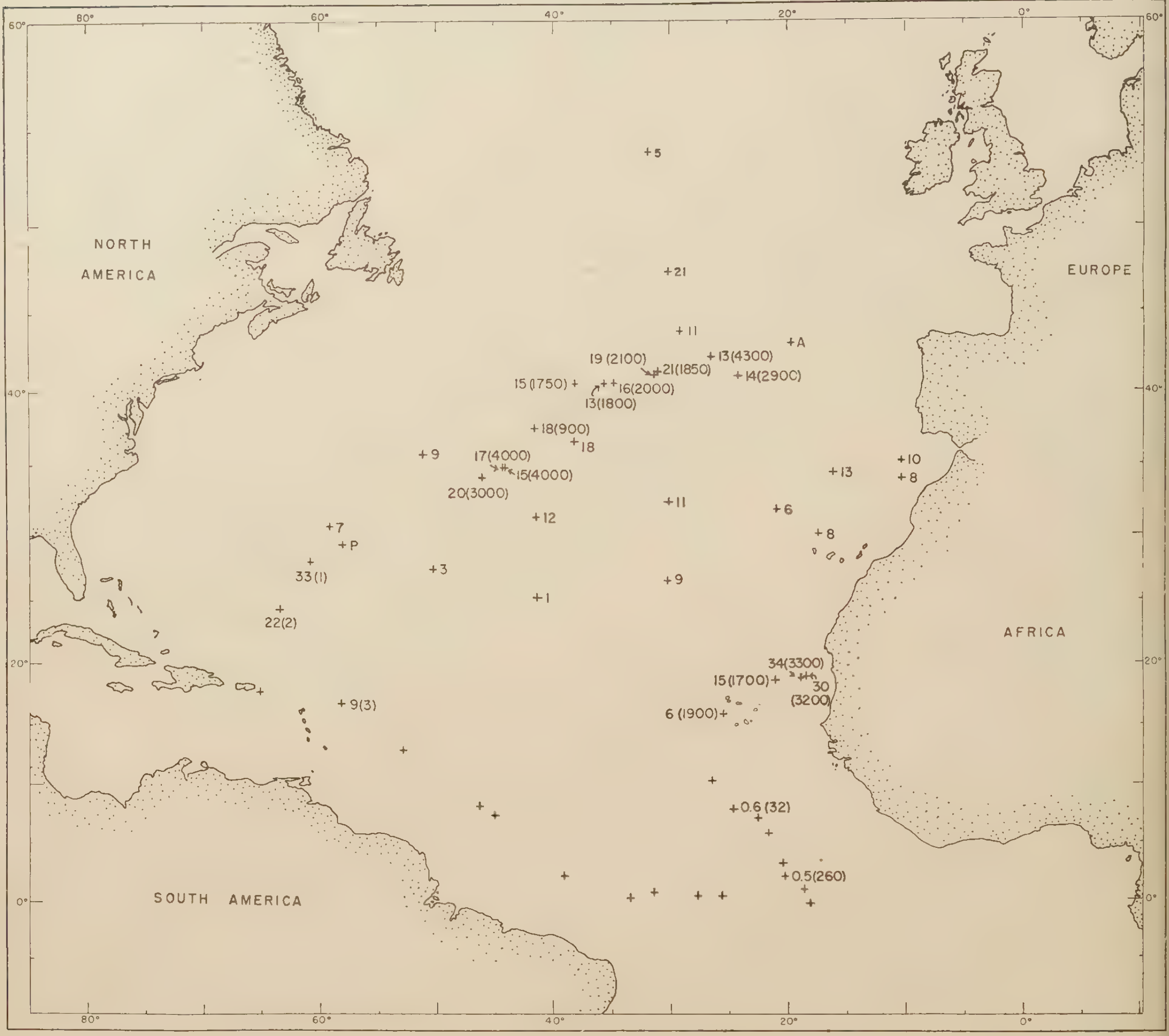
+1
+1
27(2700)
13(1400)
25(2700)
8(2700)
+6(1400)
29(26)
+20(300)
+13(1850)
8(1550)
24(1250)
11(2450)
7(3200)
+8(4700)
+12(5600)
+22(900)
6(380)
3(770)
0.7(260)
3(770)
3(2300)

ig. 4. Distribution of *Globigerina eggeri* Rhumbler in surface sediment samples. First number at each station; is per-
ent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.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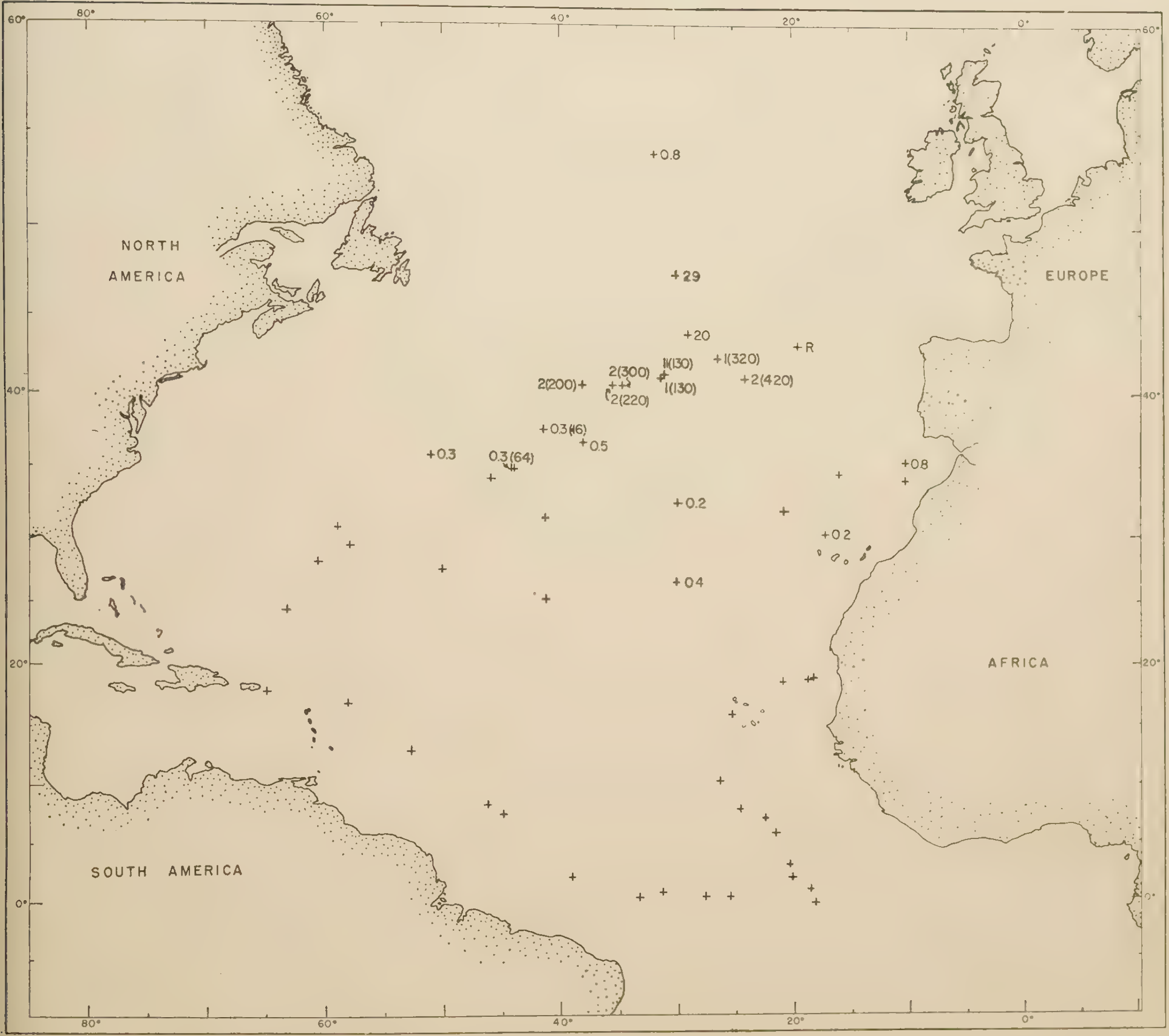
+21(1850)
+14(2900)
15 (1750) +
16(2000)
13(1800)
+18(900)
+18
+9
17(4000)
15(4000)
20(3000)
+13
+10
+8
+11
+6
+12
+7
+P
+8
33(1)
+3
+9
+1
22(2)
34(3300)
15(1700)+
30
(3200)
6 (1900)+
+9(3)
+0.6 (32)
+0.5(260)

Fig. 5. Distribution of *Globigerina inflata* d'Orbigny in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.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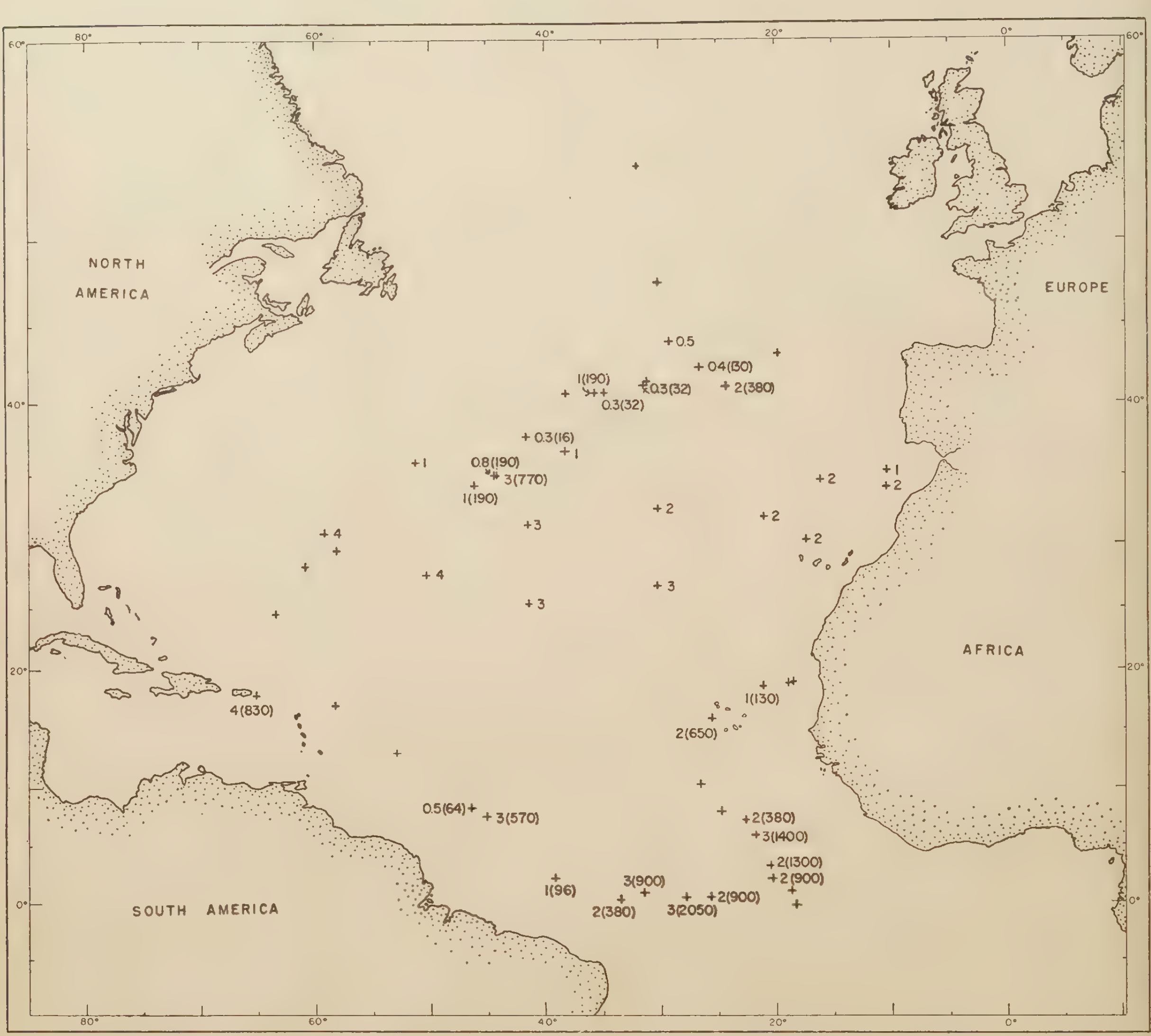
+R
+1(320)
+2(420)
1(130)
1(130)
2(300)
2(200)+
2(220)
+0.3(16)
+0.5
+0.3
0.3(64)
+0.2
+0.8
+0.2
+04

Fig. 6. Distribution of *Globigerina pachyderma* (Ehrenberg) in surface sediment samples. First number at each station s percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.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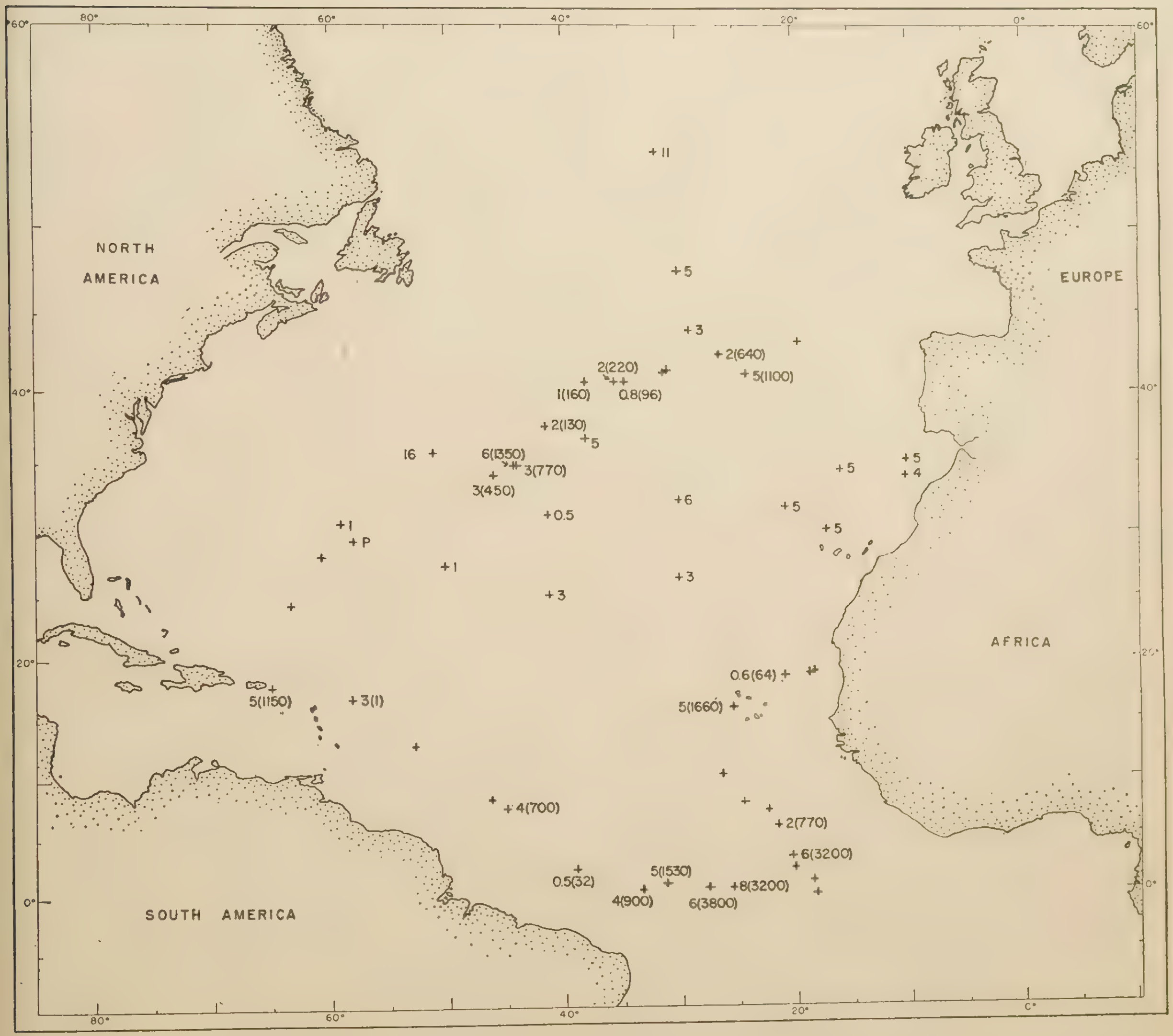
04(130)
1(190)
0.3(32)
2(380)
0.3(32)
0.3(16)
1
1
0.8(190)
3(770)
1(190)
2
1
2
2
3
2
2
4
4
3
3
1(130)
2(650)
4(830)
0.5(64)
3(570)
2(380)
3(1400)
2(1300)
2(900)
1(96)
3(900)
2(900)
2(380)
3(2050)

Fig. 7. Distribution of *Globigerinella aequilateralis* (H. B. Brady) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.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+2(640)
+5(1100)
2(220)
1(160)
0.8(96)
+2(130)
+5
16 +
6(1350)
3(770)
3(450)
+0.5
+6
+5
+5
+4
+5
+5
+1
+P
+1
+3
+3
0.6(64)
5(1660)
5(1150)
+3(1)
+4(700)
+2(770)
+6(3200)
0.5(32)
5(1530)
4(900)
6(3800)
+8(3200)

Fig. 8. Distribution of *Globigerinita glutinata* (Egger) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

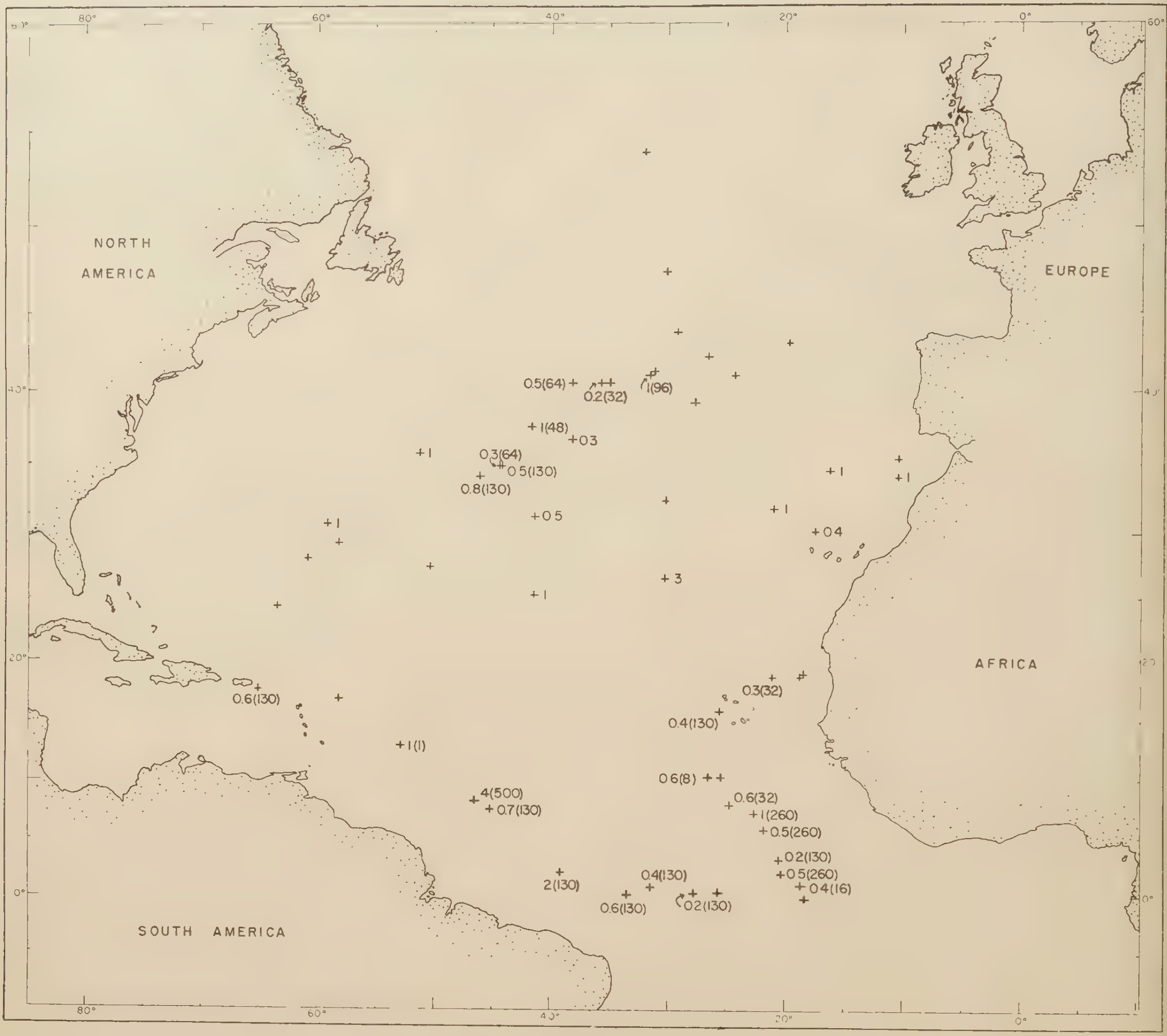

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH
AMERICA
EUROPE
AFRICA
SOUTH AMERICA
0.5(64)
0.2(32)
1(96)
+1(48)
+03
+1
0.3(64)
0.5(130)
0.8(130)
+1
+1
+05
+1
+04
+3
+1
0.6(130)
+1(1)
0.3(32)
0.4(130)
0.6(8)
4(500)
+0.7(130)
0.6(32)
+1(260)
+0.5(260)
0.2(130)
+05(260)
+04(16)
2(130)
0.4(130)
0.6(130)
02(130)

Fig. 9. Distribution of *Globigerinoides conglobata* (H. B. Brady) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

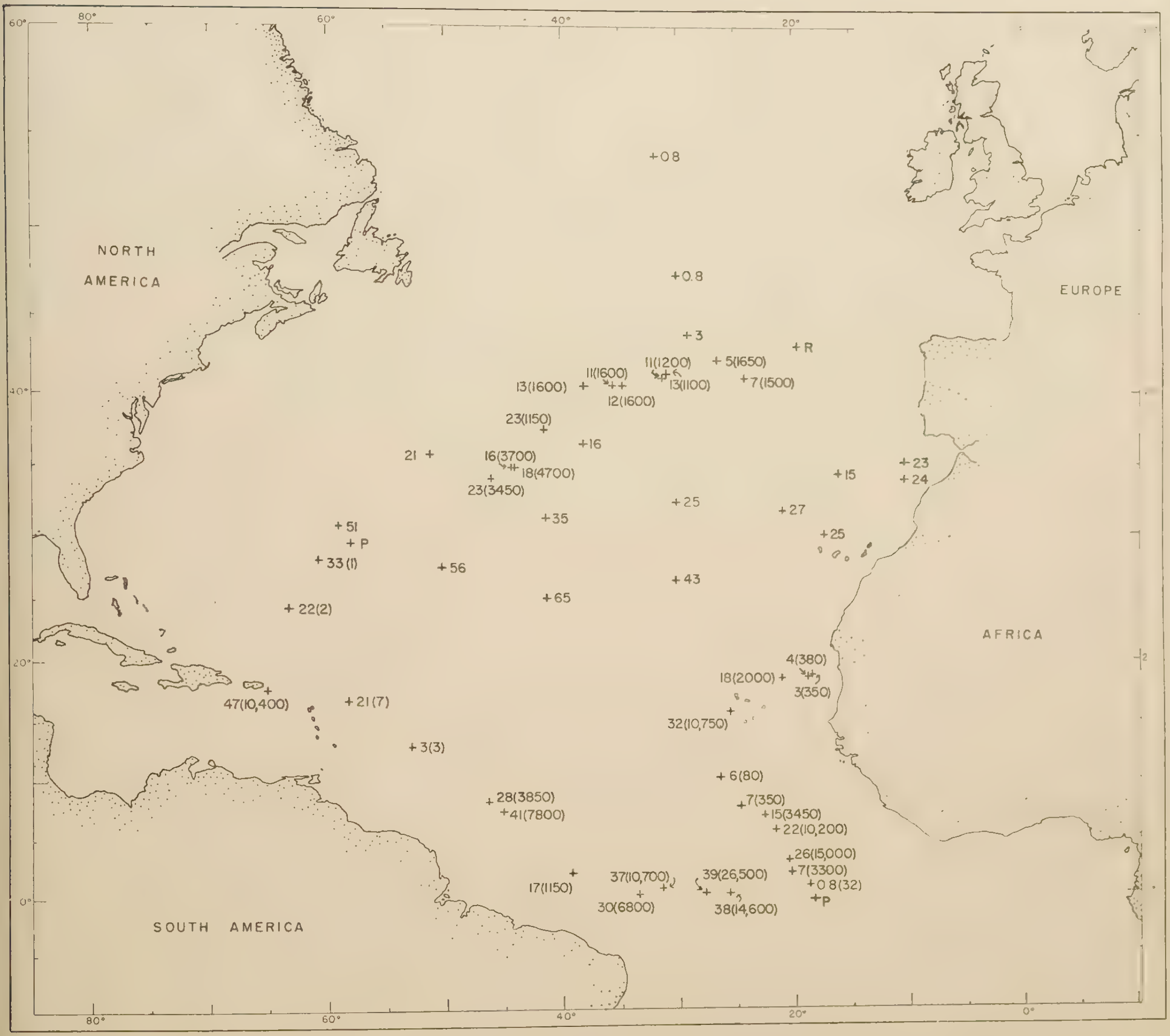

60°
80°
60°
40°
20°
NORTH
AMERICA
EUROPE
AFRICA
SOUTH AMERICA
+0.8
+0.8
+3
+R
11(1200)
+5(1650)
11(1600)
13(1600)
13(1100)
+7(1500)
12(1600)
23(1150)
+16
21
16(3700)
18(4700)
23(3450)
+15
+23
+24
+25
+27
+35
+51
+P
+33(1)
+56
+25
+43
+65
+22(2)
4(380)
18(2000)
3(350)
32(10,750)
47(10,400)
+21(7)
+3(3)
+6(80)
+7(350)
+15(3450)
+22(10,200)
28(3850)
+41(7800)
+26(15,000)
+7(3300)
+0.8(32)
+P
17(1150)
37(10,700)
39(26,500)
30(6800)
38(14,600)
40°
20°
0°
80°
60°
40°
20°
0°

Fig. 10. Distribution of *Globigerinoides rubra* (d'Orbigny) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

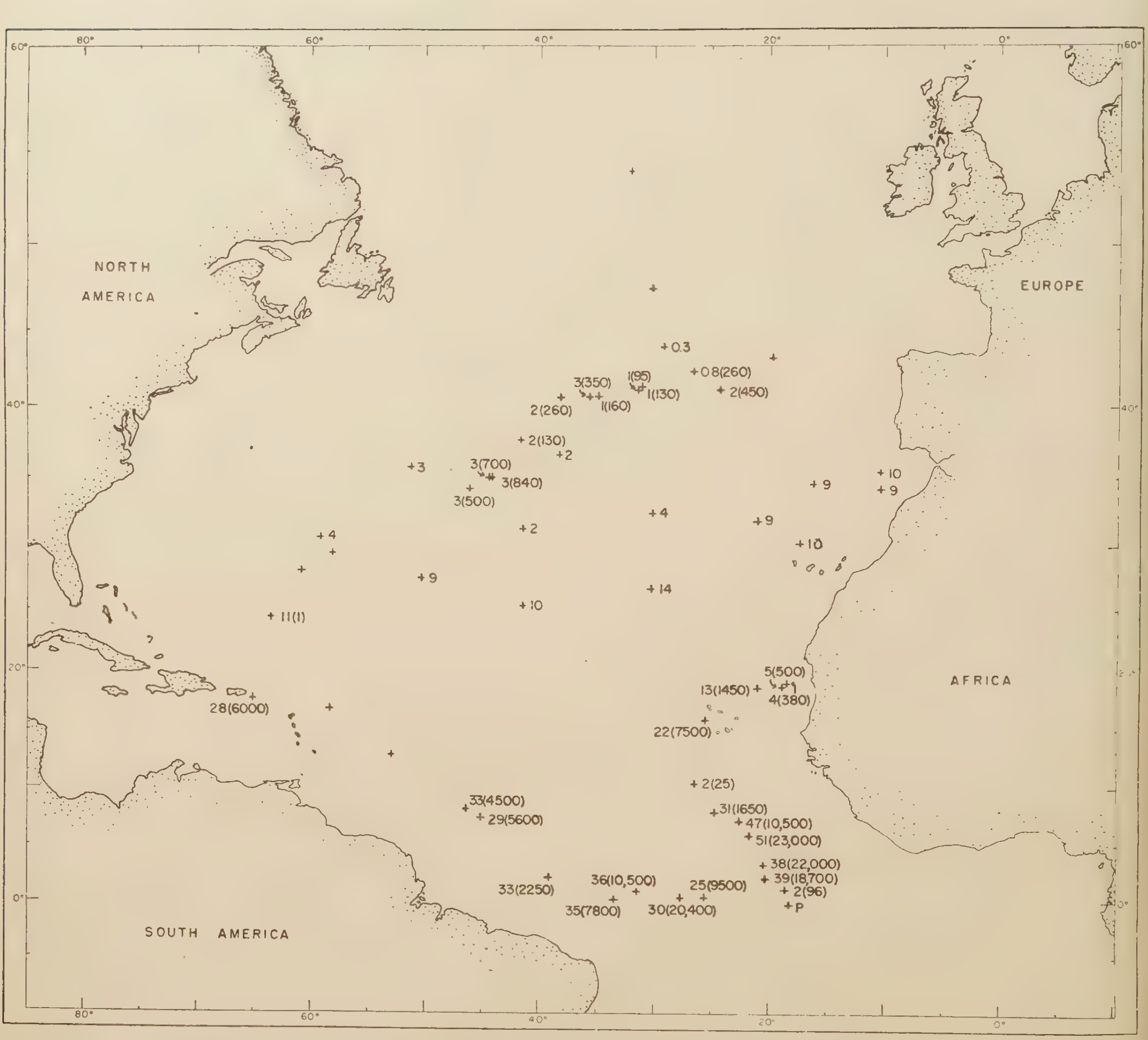

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
0.3
0.8(260)
3(350)
1(95)
1(130)
2(450)
2(260)
1(160)
2(130)
2
3
3(700)
3(840)
3(500)
9
10
9
4
9
4
2
10
9
14
10
11(1)
5(500)
13(1450)
4(380)
28(6000)
22(7500)
2(25)
33(4500)
29(5600)
31(1650)
47(10,500)
51(23,000)
38(22,000)
39(18,700)
2(96)
P
33(2250)
36(10,500)
25(9500)
35(7800)
30(20,400)

Fig. 11. Distribution of *Globigerinoides sacculifera* (H. B. Brady) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

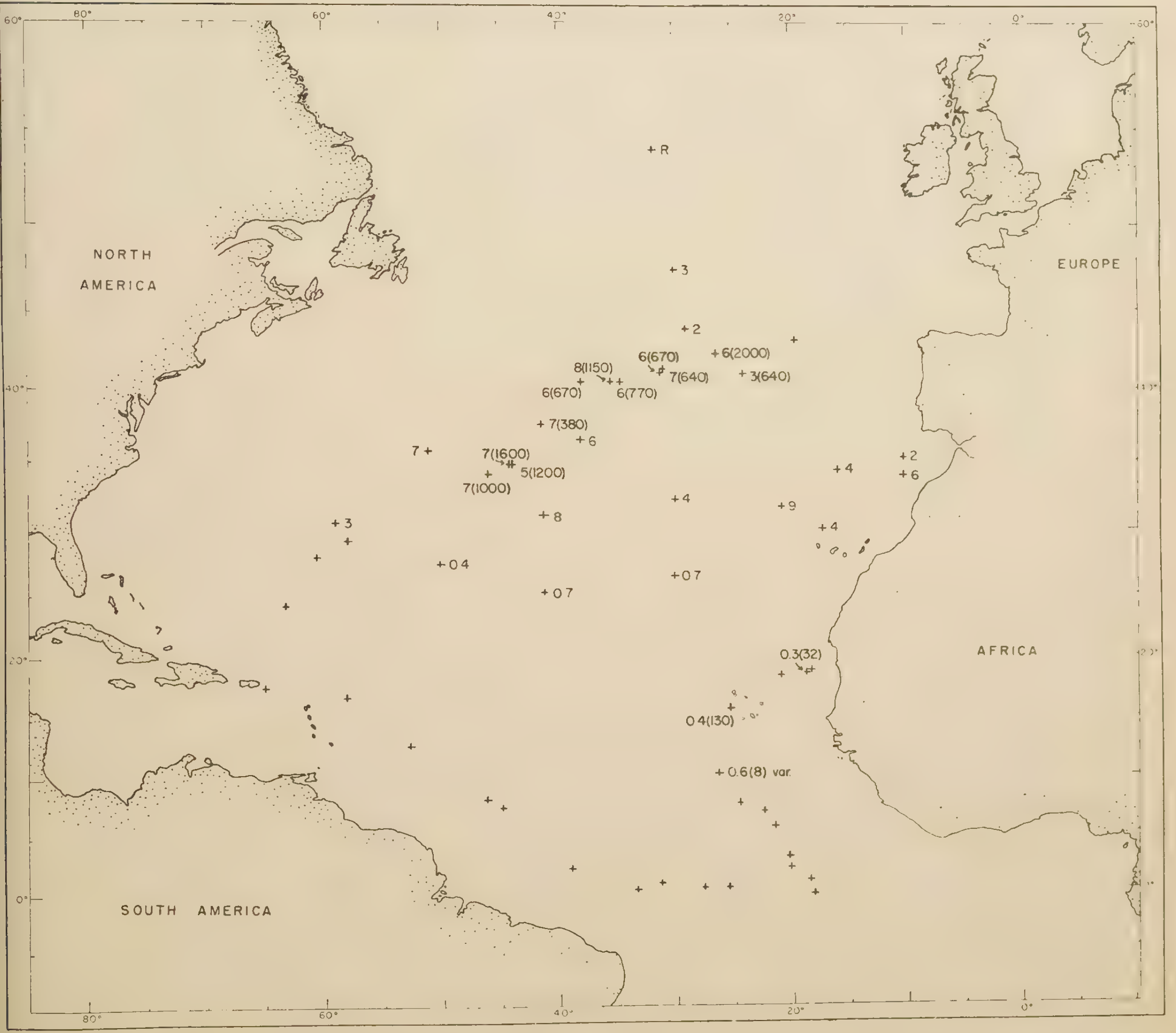

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
R
3
2
6(670)
6(2000)
8(1150)
7(640)
3(640)
6(670)
6(770)
7(380)
6
7
7(1600)
5(1200)
7(1000)
4
2
6
4
9
8
3
4
0 4
0 7
0 7
0.3(32)
0 4(130)
0.6(8) var.

Fig. 12. Distribution of *Globorotalia hirsuta* (d'Orbigny) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

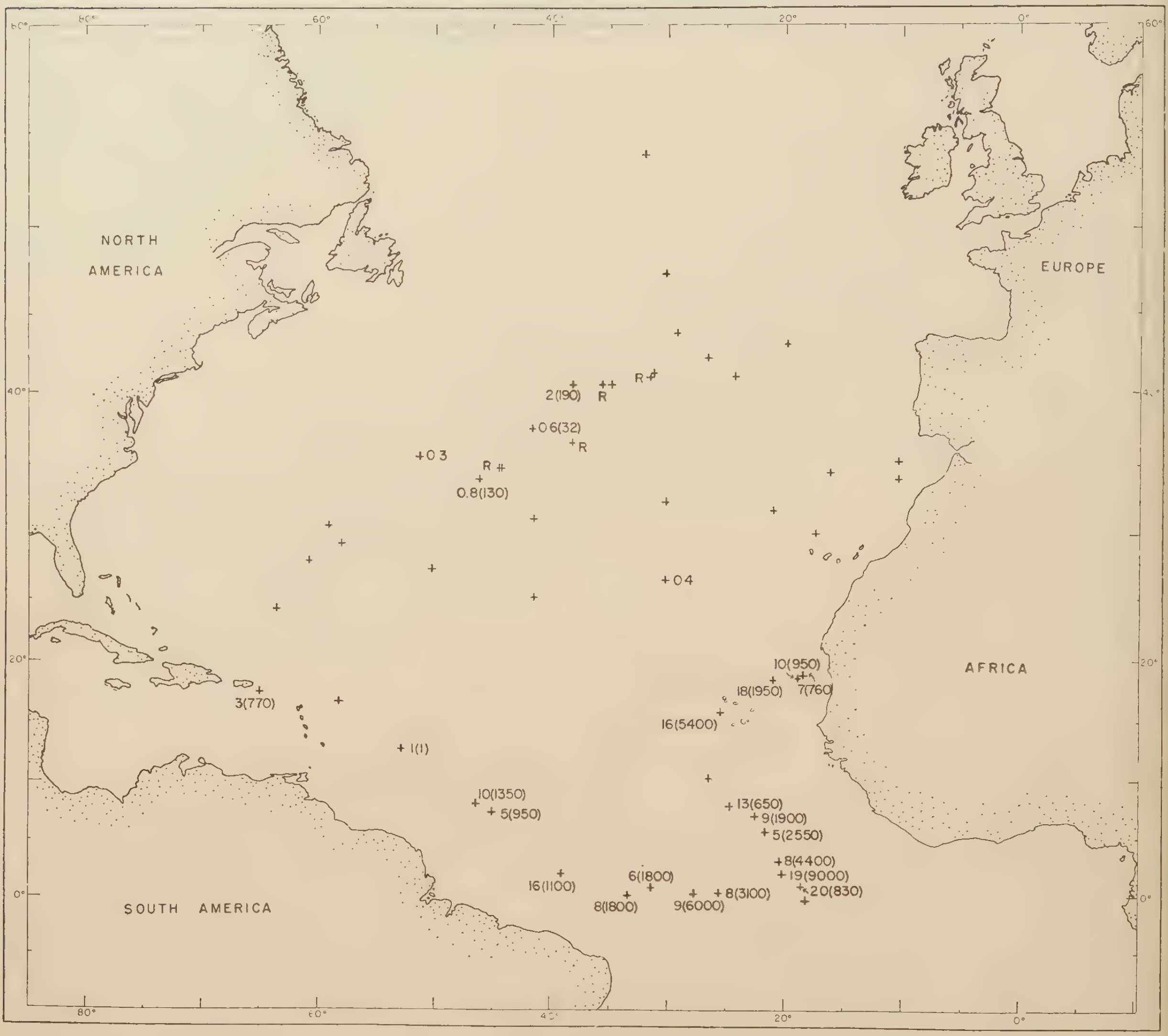
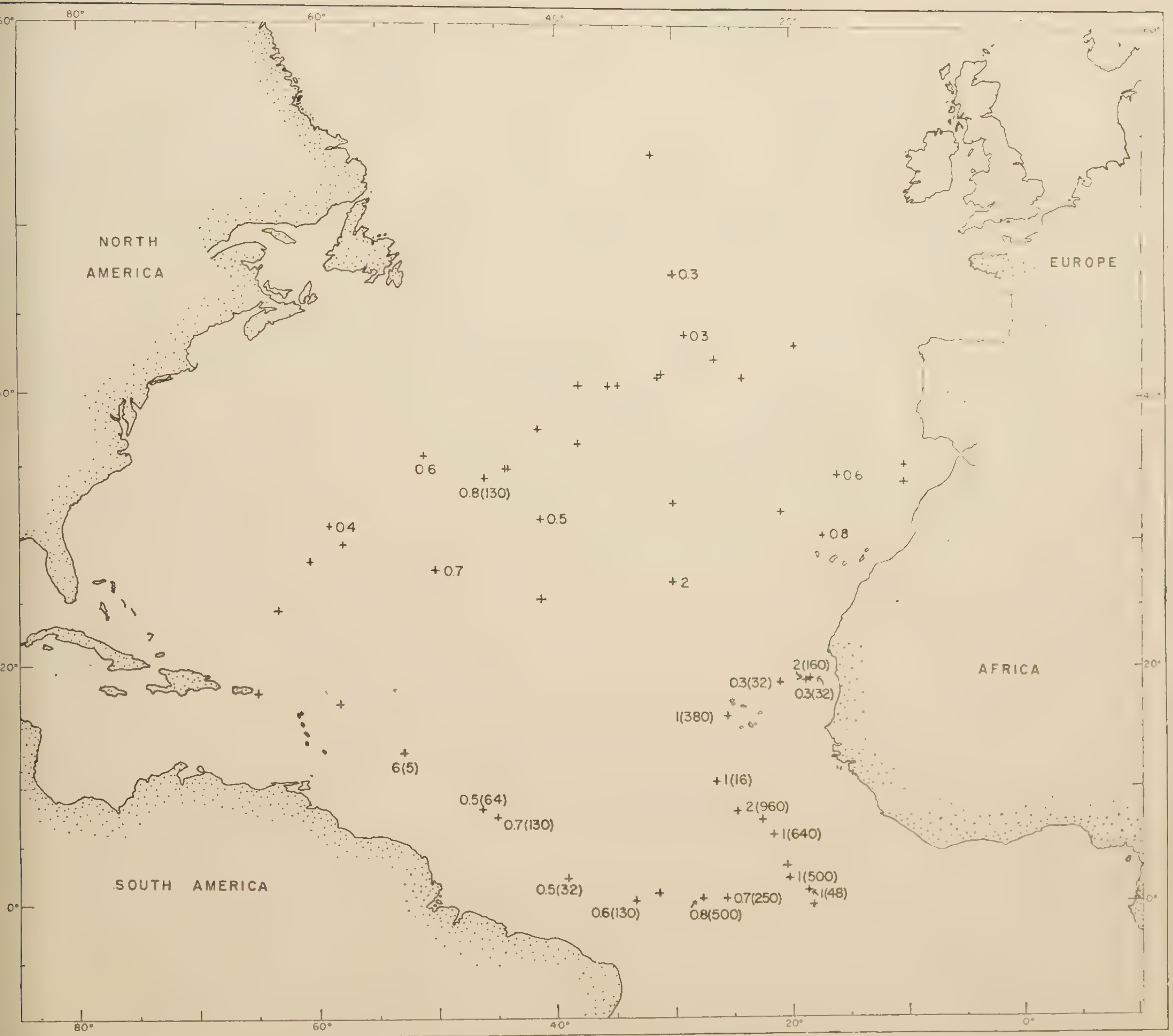

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH
AMERICA
EUROPE
AFRICA
SOUTH AMERICA
2(190)
R
R
+0 6(32)
R
+0 3
R #
0.8(130)
+0 4
10(950)
18(1950)
7(760)
16(5400)
3(770)
1(1)
10(1350)
5(950)
13(650)
9(1900)
5(2550)
8(4400)
19(9000)
20(830)
16(1100)
6(1800)
8(1800)
9(6000)
8(3100)

Fig. 13. Distribution of *Globorotalia menardii* (d'Orbigny) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.


80°
60°
40°
20°
0°
NORTH
AMERICA
EUROPE
AFRICA
SOUTH AMERICA
+0.3
+03
0.6
0.8(130)
+0.5
+04
+0.7
+2
+06
+08
2(160)
03(32)
03(32)
1(380)
6(5)
+1(16)
0.5(64)
0.7(130)
2(960)
+1(640)
+1(500)
1(48)
0.5(32)
0.6(130)
+0.7(250)
0.8(500)
20°
0°

ig. 14. Distribution of *Globorotalia punctulata* (d'Orbigny) in surface sediment samples. First number at each sation is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

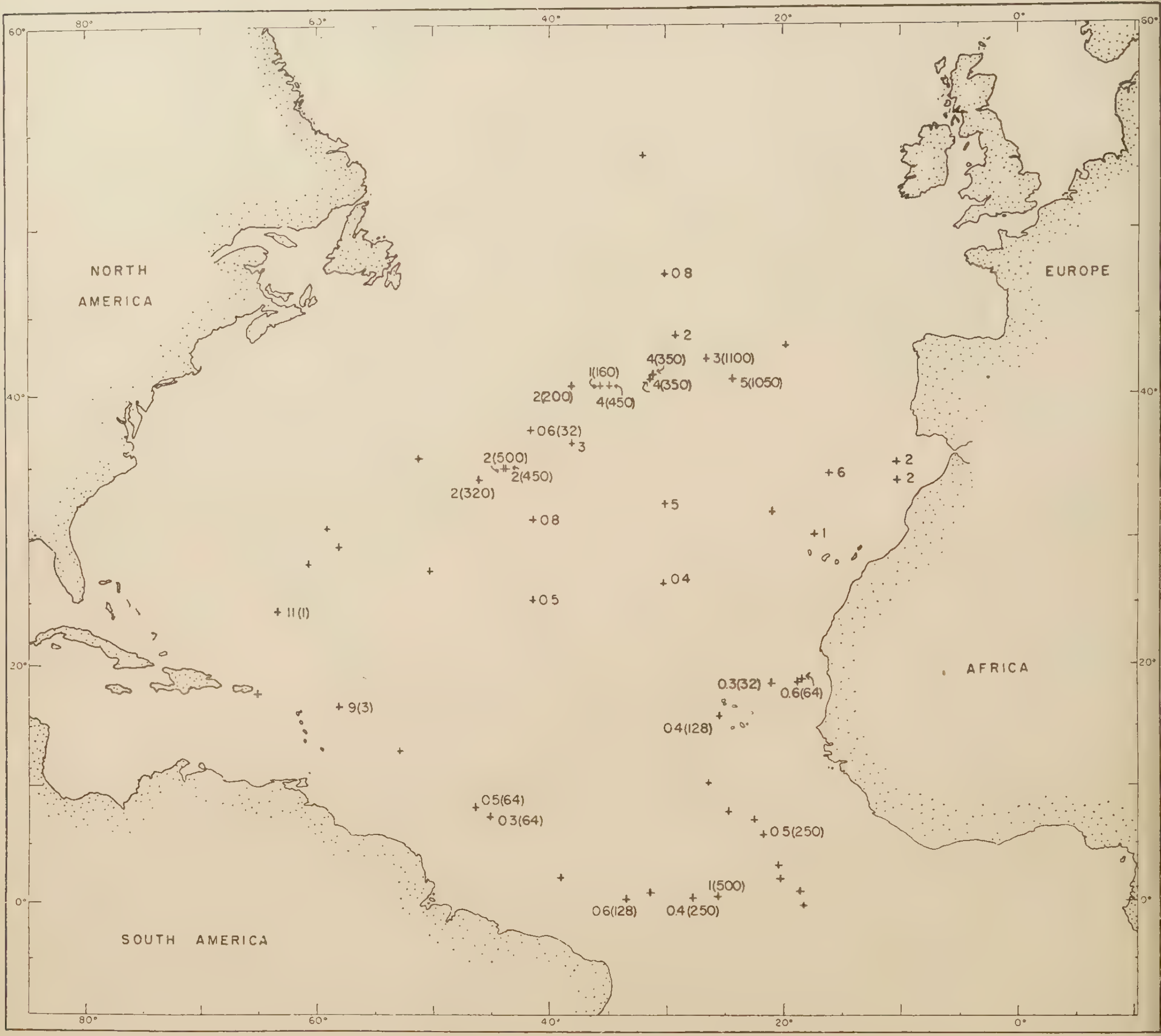

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH
AMERICA
EUROPE
AFRICA
SOUTH AMERICA
+0.8
+2
4(350)
+3(1100)
1(160)
4(350)
5(1050)
2(200)
4(450)
+0.6(32)
+3
2(500)
2(450)
2(320)
+6
+2
+2
+5
+0.8
+1
+0.4
+0.5
+11(1)
0.3(32)
0.6(64)
0.4(128)
+9(3)
0.5(64)
0.3(64)
0.5(250)
1(500)
0.6(128)
0.4(250)

Fig. 15. Distribution of *Globorotalia scitula* (H. B. Brady) in surface sediment samples. First number at each st tion is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimate actual number of specimens.

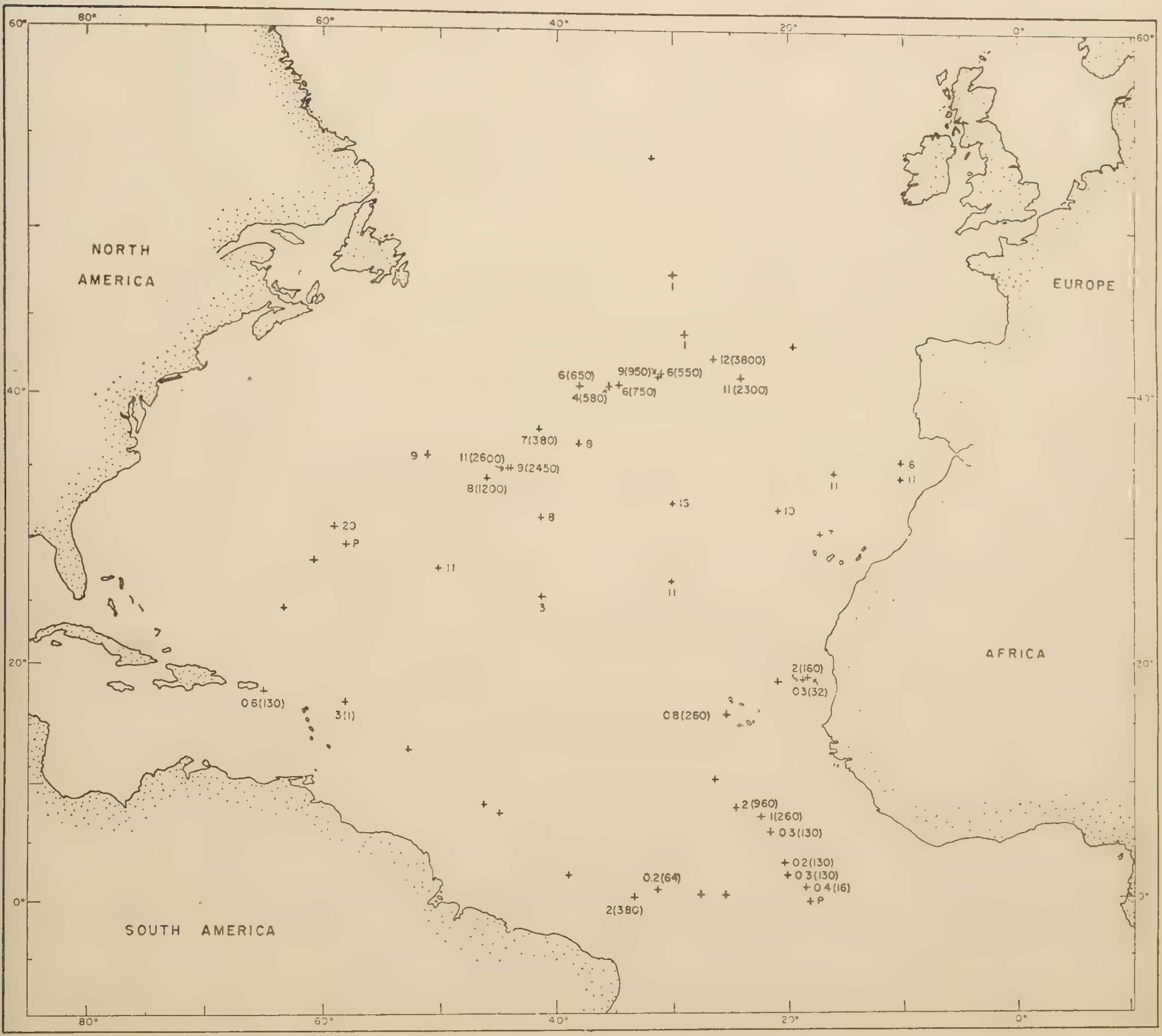

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
1
1
+ 12(3800)
6(650)
9(950)
6(550)
4(580)
6(750)
11(2300)
7(380)
+ 8
9 +
11(2600)
9(2450)
8(1200)
+ 6
+ 11
11
+ 13
+ 10
+ 8
+ 20
+ P
+ 7
+ 11
3
11
2(160)
03(32)
06(130)
3(1)
08(260)
2(960)
1(260)
03(130)
02(130)
03(130)
04(16)
+ P
0.2(64)
2(380)

Fig. 16. Distribution of *Globorotalia truncatulinoides* (d'Orbigny) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

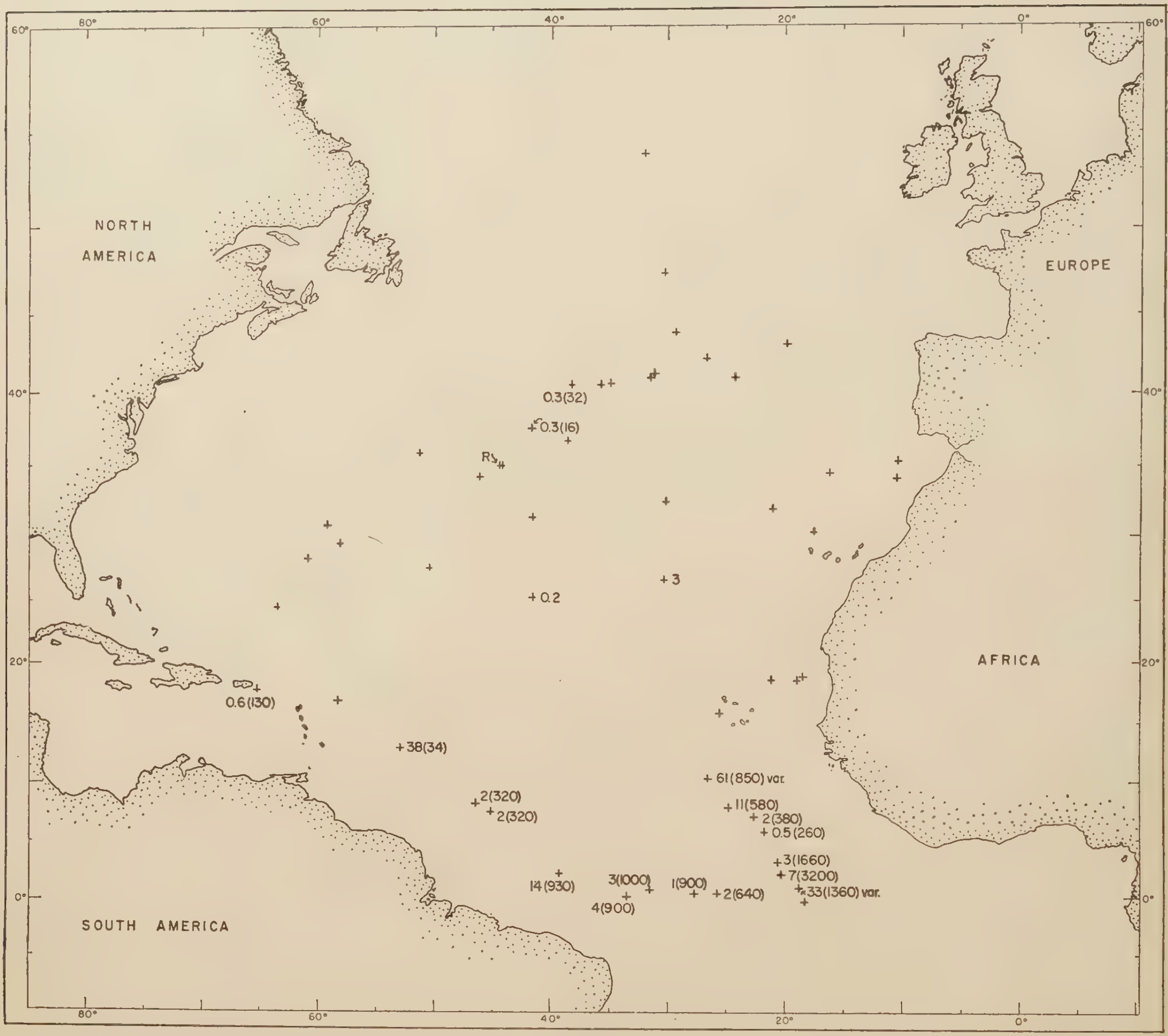
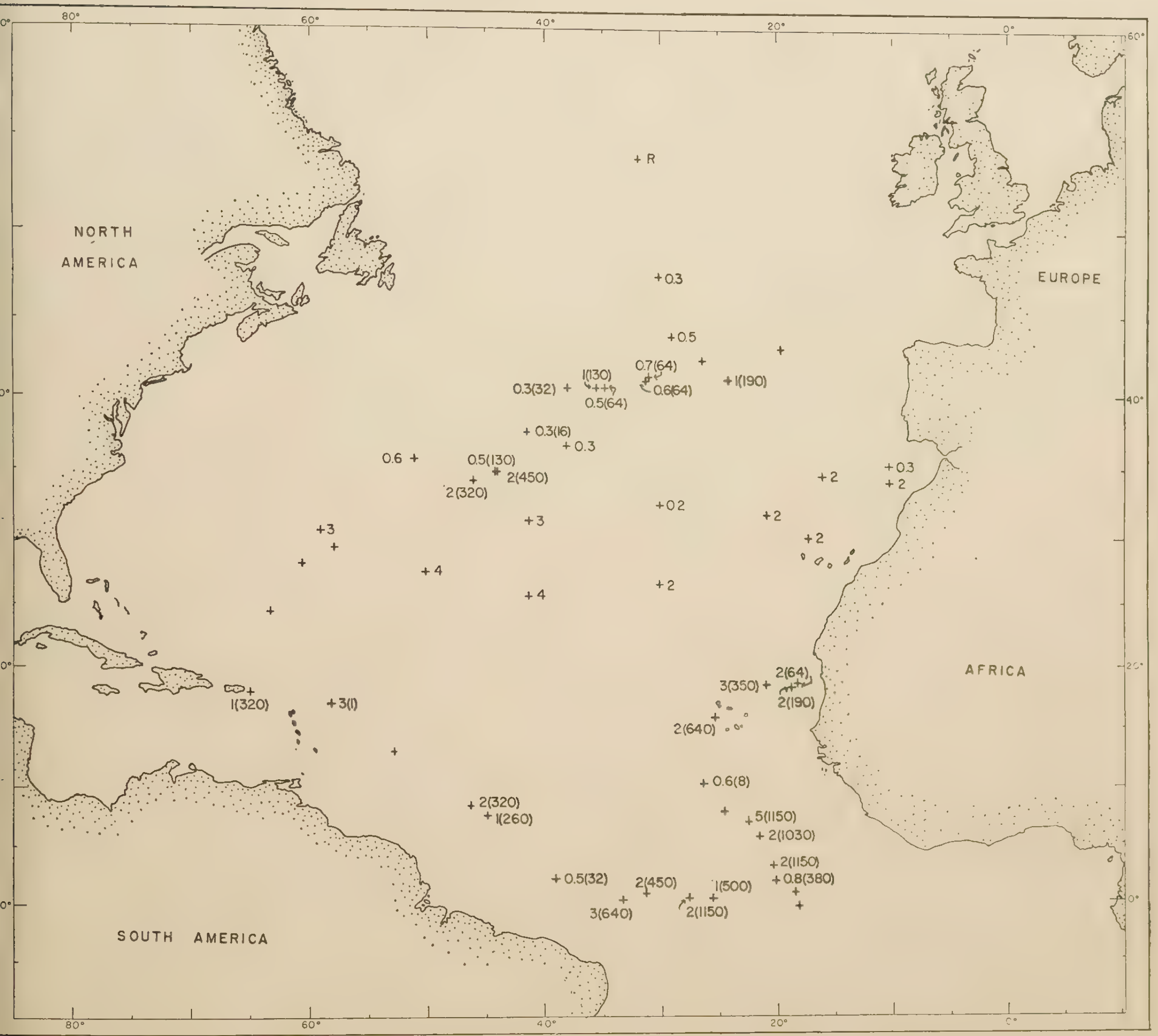

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
0.3(32)
0.3(16)
RS
+3
+0.2
0.6(130)
+38(34)
2(320)
2(320)
+61(850) var.
+11(580)
+2(380)
+0.5(260)
+3(1660)
+7(3200)
33(1360) var.
14(930)
3(1000)
4(900)
1(900)
+2(640)

Fig. 17. Distribution of *Globorotalia tumida* (H. B. Brady) in surface sediment samples. First number at each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.


NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
80°
60°
40°
20°
0°
R
0.3
0.5
0.7(64)
1(130)
0.3(32)
0.6(64)
0.5(64)
1(190)
0.3(16)
0.3
0.6
0.5(130)
2(450)
2(320)
3
0.2
2
2
0.3
2
3
4
4
2
2
3(350)
2(64)
2(190)
2(640)
1(320)
3(1)
0.6(8)
2(320)
1(260)
5(1150)
2(1030)
2(1150)
0.8(380)
0.5(32)
2(450)
1(500)
3(640)
2(1150)

g. 18. Distribution of *Orbulina universa* d'Orbigny in surface sediment samples. First number at each station is percent total population of planktonic Foraminifera; second number, in parentheses, is estimated actual number of specimens.

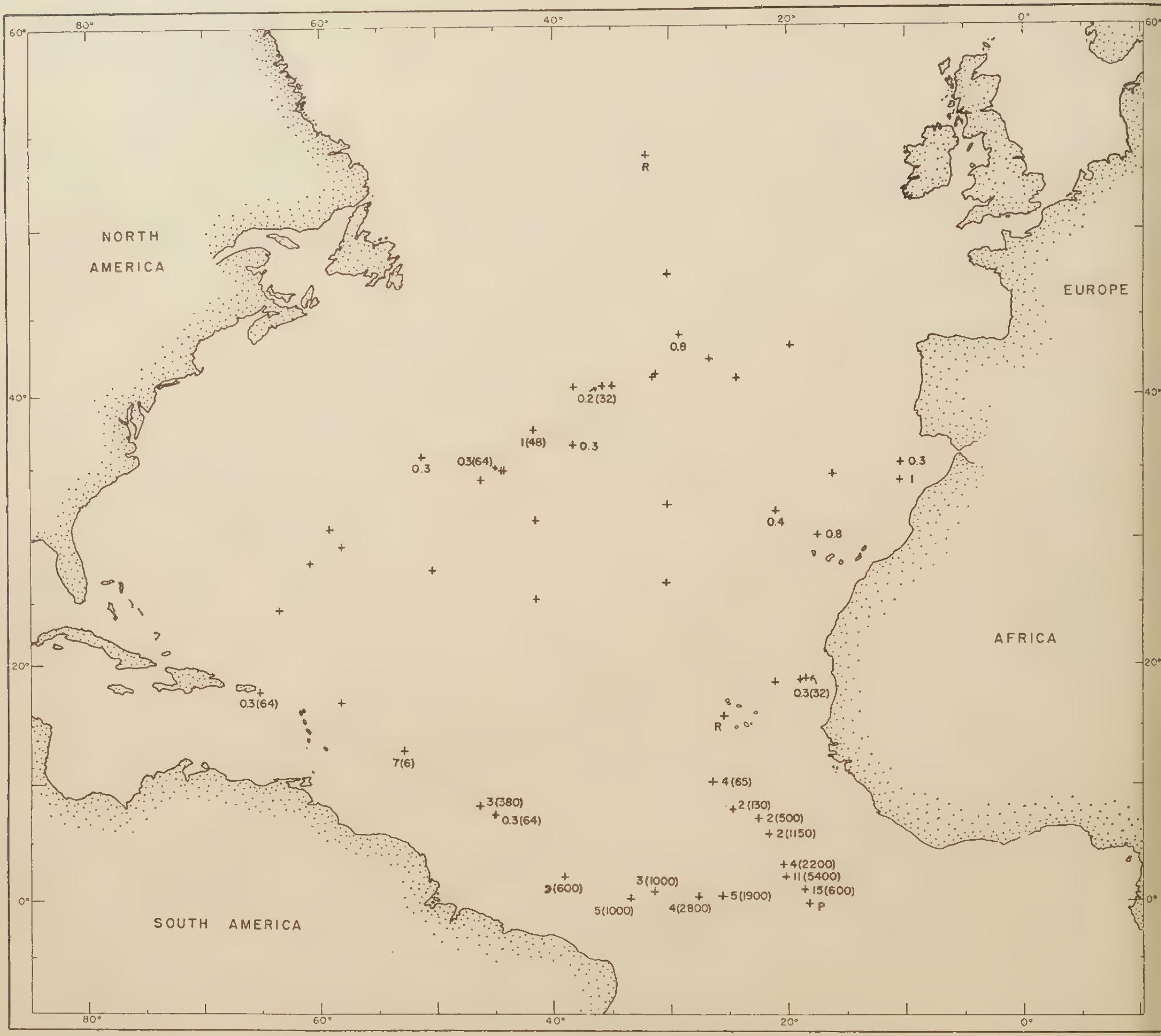

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
R
0.8
0.2(32)
1(48)
0.3
0.3
0.3(64)
0.3
1
0.4
0.8
0.3(32)
0.3(64)
R
7(6)
4(65)
3(380)
0.3(64)
2(130)
2(500)
2(1150)
4(2200)
11(5400)
15(600)
P
3(600)
3(1000)
5(1000)
4(2800)
5(1900)

Fig. 19. Distribution of *Pulleniatina obliquiloculata* (Parker and Jones) in surface sediment samples. First number each station is percent of total population of planktonic Foraminifera; second number, in parentheses, is estimate actual number of specimens.

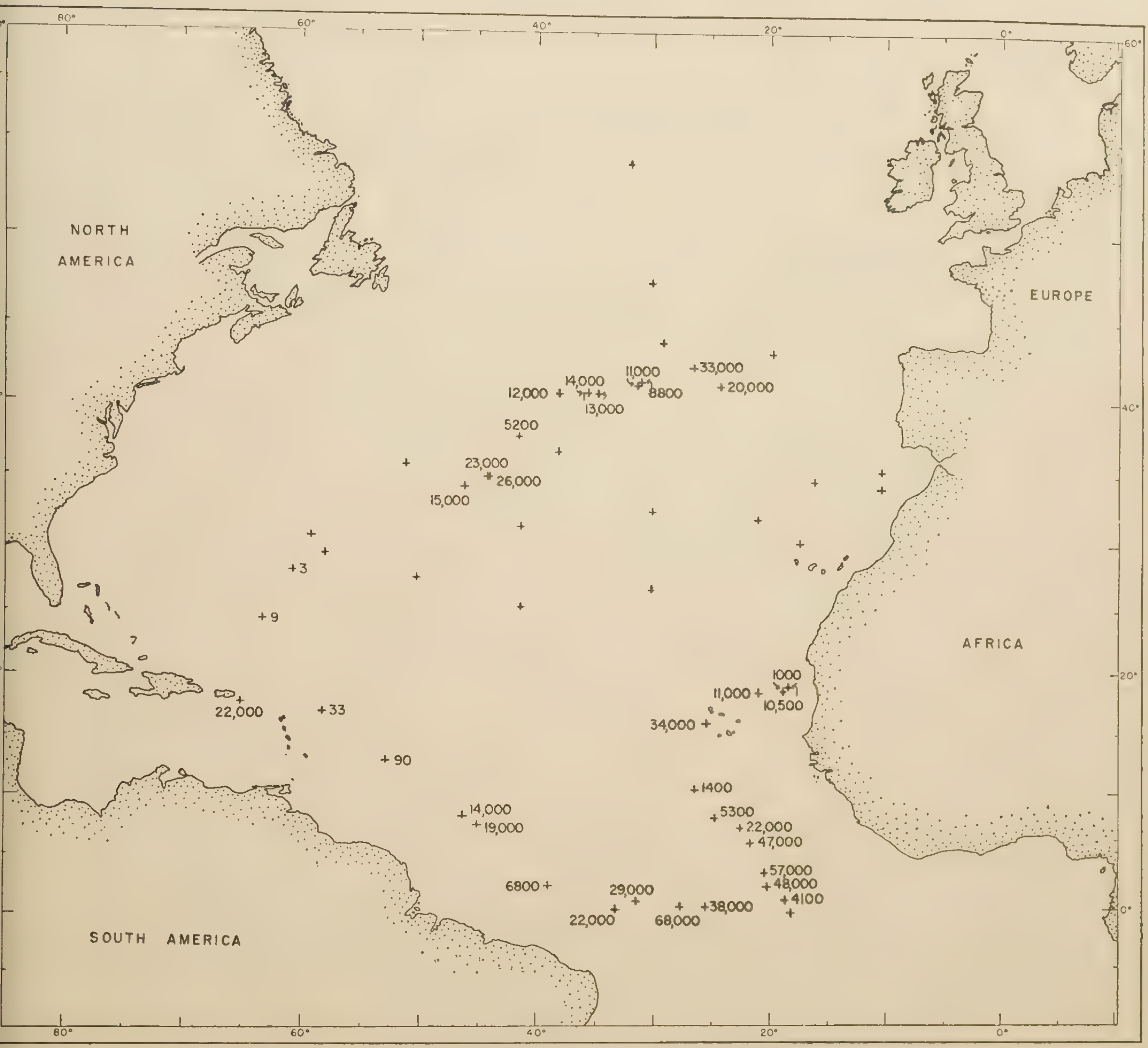

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
12,000
14,000
13,000
11,000
8800
33,000
20,000
5200
23,000
26,000
15,000
3
9
22,000
33
90
11,000
1000
10,500
34,000
1400
14,000
19,000
5300
22,000
47,000
57,000
48,000
4100
6800
29,000
22,000
68,000
38,000

Fig. 20. Total populations of planktonic Foraminifera in surface sediment samples.

northernmost ones, at low frequencies (4 % or less).

*Globigerinita glutinata* is generally distributed in the region at the majority of stations, with most frequencies 5 % or less.

*Globigerinoides conglobata* occurs at the majority of stations south of 40° N. Lat. The usual frequencies are 1 % or less.

*Globigerinoides rubra* is present at every station at relatively high frequencies, 10—65 %, except at the two northernmost stations where it is less than 1 % of the fauna. It may be most characteristic of the areas south of about 42° N. Lat.

*Globigerinoides sacculifera* is universally distributed except at the two northernmost stations. Frequencies are much higher south of approximately 10° N Lat. where they average more than 30 % at most stations. Frequencies are much lower north of this latitude where they are generally less than 10 %. North of approximately 35° N Lat. they are 3 % or less at most stations.

*Globorotalia hirsuta* appears to be characteristic of areas north of 30° N Lat., where it is 2—8 % of the fauna at each station. It is less than 1 % of the fauna at most of the stations between 10° and 30° N Lat., and it is not recorded south of 10° N Lat.

*Globorotalia menardii* is largely restricted to south of about 20° N Lat. where it occurs at frequencies of 5—20 %. It is recorded from nine mid-Atlantic stations between about 25° and 40° N. Lat. at frequencies of 2 % or less.

*Globorotalia punctulata* is recorded at most stations south of 20° N. Lat., generally at frequencies of 1 % or less. It is recorded from approximately half of the stations north of 20° N. Lat. at frequencies less than 1 %.

*Globorotalia scitula* is present in low percentages in the majority of the samples studied. The frequencies are somewhat higher north of about 32° N. Lat. (up to 6 %) than in the south, where they are all lessth an 1 %.

*Globorotalia truncatulinoides* is recorded fro almost every station. It has higher frequencie between about 25° N. Lat., and 42° N. Lat where it is 3—20 % of the population. Sout of 20 % N. Lat. the frequencies are distinctl lower than farther north, being 2 % or less the population.

*Globorotalia tumida* is essentially restricte to south of about 13° N. Lat. where it occu at variable but relatively high frequencie generally about 10 % or less but as high 61 % at one station. It is recorded at lo frequencies (less than 1 %) from 5 stations i the mid-Atlantic between 20° and 40° N. La

*Orbulina universa* is recorded from essentiall every station, constituting a low percentage the fauna (usually 2 % or less).

*Pulleniatina obliquiloculata* occurs at ever station south of approximately 13° N. La The percentages in this southern area averag about 2—5 % but are as high as 15 %. It als occurs at several more northern stations bu at distinctly lower frequencies, generally le than 1 %.

*Discussion*

In evaluating the distributions describe above and shown on Figures 3—19, the densit and locations of the sample stations shoul be taken into account. Only 53 samples we obtained, and 3 of them are unreliable becau of the small populations. It is obviously n valid to make far-reaching, definite concl sions based upon such a low-density sampli especially as there are considerable variatio in the Foraminifera populations of sampl taken nearby. This is perhaps less striki in the deep ocean basins than in nearsho areas where conditions are more variable ov short distances. Samples are difficult a expensive to obtain from the deep-sea f obvious technical reasons, and the number samples available is thus limited. The quali of samples is another limiting factor.

The frequencies of the present planktonic species seem to show geographic trends which are consistent. This suggests that it is valid to use the present samples for making limited generalizations. It also strongly suggests that the samples are comparable in method of collection and that even though the faunas may not all be modern they are at least like the modern assemblage.

Previous studies of distributions of planktonic faunas from North and equatorial Atlantic sediment samples are as follows:

Schott (1935) has reported the distributions in surface sediment samples and plankton tows from the equatorial Atlantic collected by the METEOR Expedition. Cushman and Henbest (1940) report the faunas from 10 cores in the northern area. Phleger (1942) lists faunas from a part of the western continental slope, and Parker (1948) from the adjacent continental shelf. Ovey (Wiseman and Ovey, 1950) gives the faunas from nine scattered localities in the North Atlantic. Additional information can be obtained from Brady (1884) and Cushman (1924, 1931). The distributions given in these papers are quite similar to those shown in the present study, and in general this previous work supplements the present data.

The distributions of many of the planktonic species show variations with latitude as described above. These are not sharp, but are gradational. A few generalized types of distribution are listed below:

1. The following species seem to be characteristic of low latitudes, less than 20° N. Lat., where they occur at relatively high frequencies; they also occur in low frequencies at a few stations in mid-latitudes in the central Atlantic:

   *Globorotalia menardii*
   *G. tumida*
   *Pulleniatina obliquiloculata*

2. The following species occur in much greater abundance in low latitudes than in mid-latitudes although they occur at most of the stations:

   *Globigerina eggeri*
   *Globigerinoides sacculifera*

3. *Globigerina pachyderma* is confined to high and mid-latitudes.

4. The following species are more abundant in mid-latitudes although they also occur in low latitudes:

   *Globigerina bulloides*
   *G. inflata*
   *Globorotalia hirsuta*
   *G. scitula*
   *G. truncatulinoides*

5. The following species are universally distributed in approximately uniform frequencies within the area covered in this report:

   *Globigerinella aequilateralis*
   *Globigerinita glutinata*
   *Globigerinoides conglobata*
   *G. rubra*
   *Orbulina universa*

There is an approximate correlation between distribution of surface isotherms and latitude. The distribution of the mean sea surface temperatures in the North Atlantic for August and February is shown on Figure 21, based upon the sea surface temperature charts compiled by the U. S. Hydrographic Office. It should be emphasized that while these charts are statistically correct they are broad generalizations and should be evaluated as such. They do not show actual and extreme variations in surface temperatures which undoubtedly are of primary importance in regulating the distribution of organisms such as the planktonic Foraminifera. Moreover, they do not give information on the vertical distribution of temperature which Phleger's (1951) meagre data suggest is of importance in affecting distribution of planktonic Foraminifera.

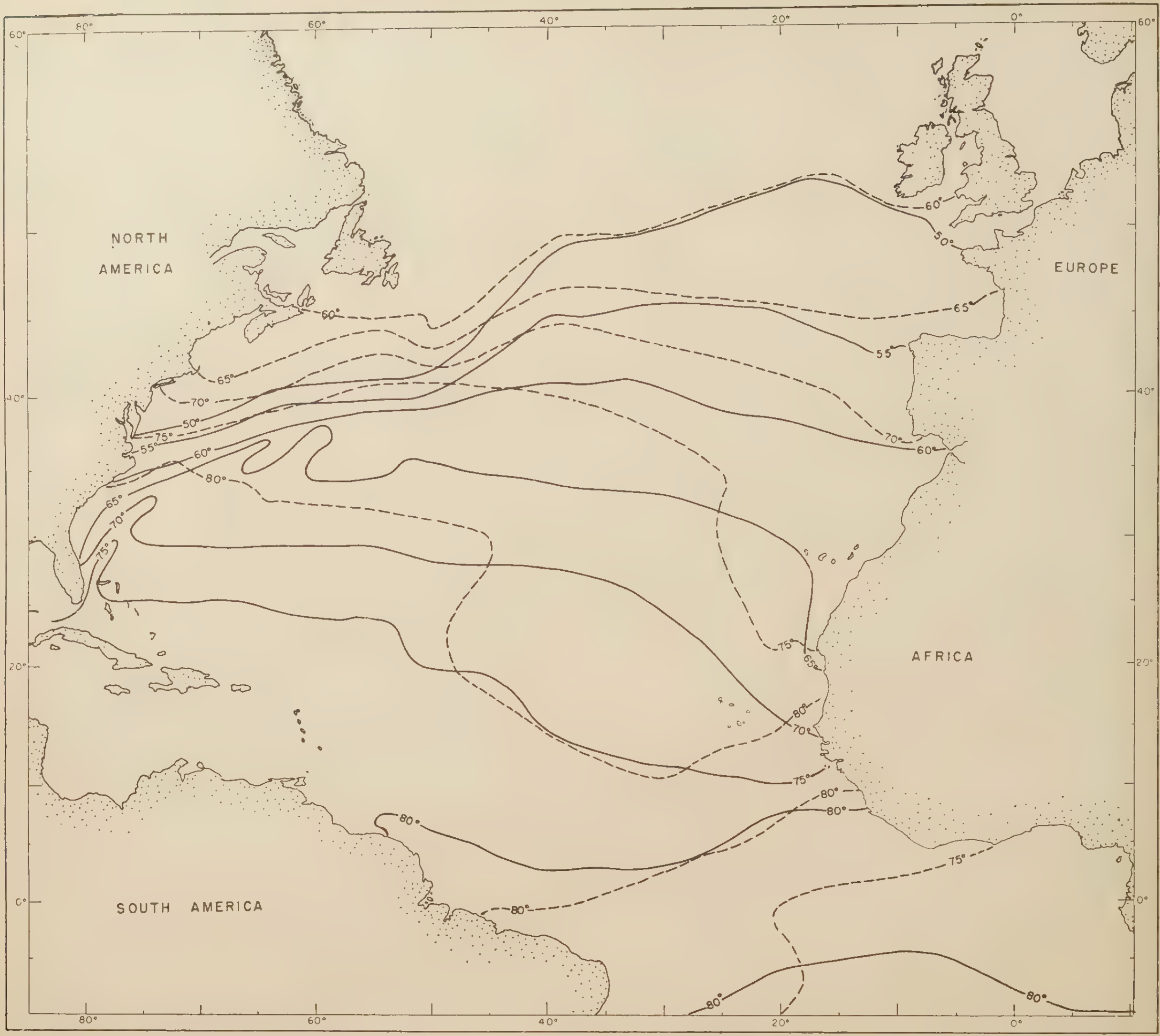


Fig. 21. Monthly mean sea surface temperatures; solid line: February; dashed line: August. (From U. S. Hydrographic Office *Atlas of Sea Surface Temperatures*).

The correlation between the distributions of species of planktonic Foraminifera and the mean monthly surface isotherms is not good in the statistical sense. It is sufficiently indicative, however, to suggest that the surface temperatures are of importance in the ecology of these species. The presence of typical low-latitude species in low frequencies in the northern part of the area covered is believed to result from the circulation pattern in the North Atlantic. It seems probable that these low-latitude specimens are carried into mid-latitudes by the tropical water masses invading those areas through the Gulf Stream system. These tropical species appear to have crossed the mean isotherms which normally constitute their northern boundary and are now deposited in a foreign latitude.

The faunal compositions of the samples in the eastern Atlantic between Cape Verde and Cape Blanco approximately 15° to 20° N. Lat. are unusual in the present suite of samples. These faunas are mixtures of many of the low-latitude and high-latitude species both of which may occur there in frequencies similar to their more usual habitat. *Globorotalia menardii* and *Globigerina eggeri* which are characteristic of low latitudes in high fre-

ncies occur in this area in similar frequen-
s; *Globigerina inflata* and *G. bulloides* are
racteristic mid-latitude species which are
ndant in the area. The total apparent
ect of these distributions is a southward
placement of the southern boundaries of
ne mid-latitude species and a northward
placement of the northern boundary of the
thern species in this area. Similar »faunal
xing» is not suggested in these latitudes on
western side of the North Atlantic, although
populations at the few stations located
re are too sparse for reliable results.

These faunas suggest that the environment
the area between Cape Verde and Cape
anco is quite variable over relatively short
riods of time. It appears that unmixed
sses of both mid-latitude and low-latitude
ter invade this area at relatively frequent
ervals and deposit their characteristic as-
nblages of planktonic Foraminifera, while
re is no suggestion of a similar mixing in
se latitudes on the western side of the
sin. The following possible explanation for
s has been suggested by Munk (personal
mmunication). This area is in the North
uatorial Current where there is a conver-
nce of Equatorial Counter Current water and
d-latitude water being brought in from
Canaries Current. These different water
sses undoubtedly carry distinctive faunas
ich are thus deposited in the form of a
ixed» assemblage. As the Equatorial Current
ws to the west these water masses are
oroughly mixed. No similar faunal mixing
to be expected on the western end of this
rrent where there is a divergence of the
uatorial water. Mixing of planktonic faunas
doubtedly is characteristic of oceanic areas
ere there is convergence of water masses; a
nilar »mixing» of faunas has been recorded
m the area of the sub-Arctic convergence
Phleger and Hamilton (1946).

These considerations, together with the five
neralized distribution types listed above, demonstrate the complex distributions of these assemblages. The ecologic factors causing these distributions are complex and very imperfectly known. In the following section the core faunas are interpreted in terms of possible sea surface temperatures which may have conditioned their occurrence. It is clear that these interpretations are tentative and are not based entirely upon presence and/or absence of any species but are based upon a series of complex relationships.

## Distribution of Foraminifera in the Cores

Most of the samples in the cores were spaced 10 cm. apart, and consisted of a half section of the wet core 5 mm. in thickness. Each sample is thus taken to represent approximately 10 cm. of sediment, and the exact boundaries of faunal differences were not located precisely.

The core faunas are listed in Tables 2 to 37 in percent of total planktonic and benthonic populations. A brief description and discussion of the major faunal features of each core is given below. Interpretations of chronology are in part based upon information on the known distribution of planktonic species from data presented in the present paper and from other studies, indicated above. Further bases for the chronology are the imperfectly known ranges of a few fossil planktonic forms and inferred possible ranges of one or two additional modern species. Interpretations of displaced assemblages are based upon known depth ranges of some of the benthonic species in addition to associations of certain species with faunas containing the species of known relatively shallow-water distribution.

### *Description of Core Faunas*

**Core 215.** The upper fauna appears to be essentially a modern one and extends through sample 2 at 10 cm. Sample 3 at 19.5—20 cm.

TABLE 2. Occurrences of Foraminifera in selected samples from Core 215 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 215 | DEPTH-4,320 M. | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 3 | 6 | 8 | 13 | 18 | 23 | 28 | 30 | 32 | 33 | 38 | 43 | 46 | 48 | 50 | 54 |
| CM. FROM TOP OF CORE | 1-1.5 | 19.5-20 | 49.5-50 | 69.5-70 | 119.5-120 | 169.5-170 | 219.5-220 | 269.5-270 | 289.5-290 | 309.5-310 | 319.5-320 | 369.5-370 | 419.5-420 | 449.5-450 | 469.5-470 | 489.5-490 | 529.5-530 |
| PLANKTONIC POPULATION | 6,200 | 14,200 | 19,500 | 49,300 | 95,600 | 650 | 39,800 | 15,700 | 64,800 | 36,300 | 52,400 | 21,400 | 3,200 | 25,200 | 46,700 | 25,900 | 38,100 |
| Globigerina bulloides | 23 | 33 | 32 | 42 | 33 | 20 | 25 | 26 | 18 | 21 | 21 | 27 | 19 | 24 | 2 | 8 | 3 |
| G. digitata | .3 | | | .3 | | | | | | .3 | | | | | | | |
| G. eggeri | 7 | 16 | 13 | 13 | 10 | 1 | 5 | 2 | 3 | 5 | 10 | 5 | 5 | 15 | 14 | 17 | 13 |
| G. hexagona | | | | | | | | | | .3 | | | | | | | |
| G. inflata | 14 | 18 | 20 | 21 | 20 | 25 | [illegible] | 22 | 20 | 22 | 24 | 18 | 21 | 16 | 29 | 27 | 28 |
| G. pachyderma | | 2 | 6 | 2 | 3 | 3 | 2 | .8 | 2 | .8 | 3 | 6 | 8 | 3 | 8 | 7 | 6 |
| G. quinqueloba | .6 | | .3 | | | .3 | | | | | 4 | | .5 | .4 | | | |
| Globigerinella aequilateralis | 2 | 3 | 1 | 1 | .5 | .6 | 2 | 1 | .4 | 1 | .7 | 1 | | 2 | | | .3 |
| Globigerinita glutinata | 6 | 2 | 2 | 3 | 10 | 6 | 5 | 10 | 7 | 9 | 3 | 7 | 9 | 6 | 2 | 3 | 1 |
| Globigerinoides conglobata | | .5 | .3 | | 2 | 2 | 2 | .8 | .8 | 1 | .7 | .3 | 2 | 2 | .3 | 1 | 1 |
| G. rubra | 23 | 17 | 16 | 9 | 12 | 20 | 17 | 11 | 24 | 27 | 28 | 20 | 20 | 21 | 11 | 12 | 10 |
| G. sacculifera | 10 | 2 | .7 | | | .6 | 1 | .4 | 6 | 4 | 3 | | .8 | 3 | 8 | 3 | 9 |
| Globorotalia hirsuta | 2 | .5 | .3 | .8 | 1 | .6 | 4 | 4 | 4 | 1 | .7 | 4 | 4 | .8 | 2 | 4 | 2 |
| G. menardii-tumida group | | | | | | | | | | 3 | .4 | | | 2 | .3 | | .3 |
| G. punctulata | | | .3 | | | | | | | | | | | | 1 | 1 | .7 |
| G. scitula | .3 | .7 | 2 | | 3 | 3 | .6 | .4 | .8 | .3 | | 1 | .5 | | | | |
| G. truncatulinoides | 10 | 4 | 4 | 5 | 5 | 7 | 9 | 21 | 11 | 7 | 3 | 9 | 10 | 5 | 20 | 13 | 23 |
| G. sp. 2 | | | | | | | | | | | | | | | .3 | | .7 |
| Orbulina universa | 2 | 1 | .5 | .3 | .8 | 1 | 1 | .8 | | 1 | 3 | 2 | 1 | 2 | 2 | .5 | 2 |
| Pulleniatina obliquiloculata | | | | | | | | | 3 | | | | | | .5 | .5 | .7 |
| [Sphaeroidina bulloides] | | | | | | | | | | | | | | | | | |
| Sphaeroidinella dehiscens | | | | | | | | | | | | | | | | | .3 |
| BENTHONIC POPULATION | 13 | 40 | 40 | 70 | 75 | 3 | 90 | 90 | 80 | 30 | 40 | 75 | 10 | 450 | 450 | 200 | 300 |
| Amphistegina lessonii | | | | | | | | | | | | | | | | 4 | |
| Anomalina sp | | | | | | | | | 1 | | | | | | 1 | | |
| Bolivina tortuosa | | 5 | | | | | | | 1 | | | | | | | | |
| Bulimina alazanensis | | | | | | | | 2 | | | | | | | | | |
| B. mexicana | | | | | | | | | | | | | | 4 | 1 | | 1 |
| Cassidulina crassa | | 8 | | | | | | | | | | | | 2 | 2 | 1 | |
| C. subglobosa | | 7 | | | 7 | | 4 | 3 | 7 | | 3 | 4 | | 2 | 2 | 6 | 8 |
| C. sp. 1 | | | | | | | | | | | | | | 7 | 2 | 4 | 7 |
| Cibicides lobatulus | | | | | | | | | | | 3 | | | 43 | 35 | 14 | 34 |
| C. refulgens | | | | | | | | | | | | | | | | 17 | 4 |
| C. robertsonianus | 8 | 3 | | | 3 | | 2 | 7 | 5 | | 6 | | | 1 | | | |
| Discorbis mamilla | | | | | | | | | | | | | | 2 | | 1 | |
| D. williamsoni | | 3 | | | | | | | | | | | | | | | |
| D. obtusa | | | | | | | | | | | | | | 7 | 6 | 5 | |
| Ehrenbergina undulata | | | | | | | | | 1 | | | | | | 1 | 2 | 3 |
| Elphidium complanatum | | | | | | | | | | | | | | 4 | | 3 | |
| E. crispum | | | | | | | | | | | | | | 1 | 13 | 9 | 15 |
| Eponides umbonatus and variants | | 10 | 13 | 10 | 16 | 33 | 8 | 5 | 1 | | 6 | 25 | 12 | 1 | 1 | 6 | 4 |
| Gyroidina lamarckiana | | | | | | | | 1 | | 4 | 3 | | | | | | |
| G. orbicularis | | | | | | | 2 | | 1 | | | | | | | | |
| G. soldanii variant | | | | | 3 | | 1 | | 1 | | 6 | 4 | | | 3 | 1 | |
| Hoglundina elegans | | | | | | | | | | | | | | | 1 | 5 | |
| Eggerella bradyi | 15 | 8 | 10 | 9 | 8 | | 19 | 20 | 12 | 4 | 3 | 9 | | 2 | 3 | | 1 |
| Laticarinina pauperata | | | | | | | | | | | | | | | 1 | 1 | |
| Miliolids | | | | | | | | | | | | | | | 6 | | |
| Nonion barleeanum | | | | | | | | | | | | | | 3 | 1 | 1 | 1 |
| N. formosum | | 3 | 3 | 2 | | | 1 | 8 | 4 | 4 | | 3 | | | | 2 | |
| N. germanicum | | | | | | | | | | | | | | 1 | | 1 | 1 |
| N. pompilioides | | 3 | 3 | 2 | 3 | | 2 | | | | | 3 | | 1 | | 3 | |
| Nummoloculina irregularis | | | | | | | | | | | | | | 2 | | | |
| Osangularia cultur | | | | | | | | | | | | | | 1 | | | |
| Planorbulina mediterranensis | | | | | | | | | | | | | | 1 | 1 | | 1 |
| Planulina ariminensis | | 3 | | | | | | | | | | | | 1 | 2 | 7 | 4 |
| P. wuellerstorfi | 15 | 3 | 8 | 19 | 17 | 33 | 16 | 9 | 10 | 21 | 22 | 12 | 38 | 2 | 6 | 6 | 8 |
| Epistominella exigua | 8 | 5 | 18 | 15 | 13 | | 8 | 10 | 18 | 14 | 20 | 13 | 38 | 2 | 1 | | |
| E. umbonifera | 23 | 5 | 15 | 27 | 16 | | 15 | 4 | 7 | 18 | 22 | 9 | 12 | 1 | 1 | | |
| Pullenia bulloides | 8 | | 13 | | 10 | 33 | 5 | 3 | 6 | 11 | 3 | 4 | | 2 | 2 | 1 | |
| P. quinqueloba | | | | | | | 1 | | 1 | | | 1 | | 1 | 1 | 1 | |
| P. sp. | | 3 | | | | | | | | | | | | | | | |
| Pyrgo murrhina | 23 | | 3 | 2 | 1 | | 5 | 4 | 9 | 4 | 3 | 9 | | 4 | | | |
| Quinqueloculina venusta | | | 8 | 6 | 3 | | 2 | 1 | | | 3 | 1 | | | | | |
| Q. cf. weaveri | | | 3 | | | | 1 | | 1 | 11 | | | | | | | |
| Robulus | | | | | | | | | | 4 | | | | | | | 1 |
| Sigmoilina tenuis | | | | | | | | | | 4 | | | | | | | |
| Siphotextularia rolshauseni | | 3 | | 2 | | | | | | 4 | | 1 | | | | | |
| Uvigerina auberiana and variant | | | | | | | | | | | | | | 3 | | | |
| U. hollicki | | | | | | | | 23 | 9 | | | | | 1 | 5 | | 5 |
| U. hollicki | | | | | | | | | | | | | | | | | |
| Valvulineria humilis | | 28 | 3 | 7 | 3 | | 6 | | | | | | | | | | |
| Virgulina bradyi | | | | | | | | | 1 | | | | | 1 | | | |
| V. complanata | | 3 | 3 | | | | | | 1 | | | | | | | | |

contains displaced material evidenced by the presence of *Bolivina tortuosa* and *Discorbis williamsoni*. These species are generally of shallow water origin, from depths less than about 200 m., and it appears that the sediment ha originated at these depths. *Planulina arim nensis* in this sample occurs in the Gulf c Mexico at depths less than 500 m. An examination of the core shows a series of layers c fine sand in the upper 42 cm. It seems possibl that these upper layers are entirely displaced although there is no additional faunal evidenc for this. From 49.5 cm. through 220 cm. th planktonic fauna may be characteristic of more northern assemblage as shown by th following: a decrease in frequency of *Globigerinoides sacculifera* and an increase of *Globigerina bulloides* in sample 8, a decrease i *Globorotalia truncatulinoides* and a decrease i *Globigerina eggeri* in the lower part of thi section. Sample 30 at 289.5—290 cm. probabl is a displaced fauna, as shown by the presenc of *Bolivina tortuosa*. Another displaced fauna is suggested questionably in sample 33 a 319.5—320 cm. by the presence of *Cibicide lobatulus*, and it is possible that the displaced layer occurs between 289.5 and about 360 cm. From 369.5 to 420 cm. the planktonic fauna appears to be normal for the latitude. The faunas from 449.5 cm. to the bottom of the core at 539 cm. are clearly displaced from shallow water, as shown by the presence of the relatively shallow-water benthonic species: *Amphistegina lessoni*, *Bulimina mexicana*, *Cassidulina sp.* 1, *Cibicides* cf. *refulgens*, *Discorbis mamilla*, *D. obtusa*, *Elphidium complanatum*, *E. crispum*, *Nummoloculina irregularis* and *Planorbulina mediterranensis*.

**Core 217.** Visual examination of this core shows several thin sand partings. Sample 17 at 159.5—160 cm. contains one specimen of *Bulimina aculeata* and sample 77 at 759.5—760 cm. contains one specimen of *Bolivina pseudoplicata*. These two species are questionably indicative of water shoaler than the postion of this core. It is suggested that the sands and isolated occurences of these two species probably represent small terminal ends

TABLE 3. Occurrences of Foraminifera in selected samples from Core 217 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 217 | DEPTH - 4,360 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 10 | 15 | 17 | 20 | 22 | 27 | 29 | 33 | 34 | 36 | 40 | 45 | 48 | 50 | 51 | 53 | 55 | 56 | 57 | 59 | 63 | 65 | 66 | 68 | 70 | 75 | 77 | 80 |
| CM. FROM TOP OF CORE | 1.5-2 | 39.5-40 | 89.5-90 | 139.5-140 | 159.5-160 | 189.5-190 | 209.5-210 | 259.5-260 | 279.5-280 | 319.5-320 | 329.5-330 | 349.5-350 | 389.5-390 | 439.5-440 | 469.5-470 | 489.5-490 | 499.5-500 | 519.5-520 | 539.5-540 | 549.5-550 | 559.5-560 | 579.5-580 | 619.5-620 | 639.5-640 | 648.5-649 | 669.5-670 | 689.5-690 | 739.5-740 | 759.5-760 | 789.5-790 |
| PLANKTONIC POPULATION | 9,300 | 11,000 | 1,800 | 9,000 | 19,800 | 17,600 | 29,000 | 9,700 | 11,900 | 3,300 | 12,100 | 7,800 | 12,200 | 1,500 | 6,800 | 2,350 | 5,400 | 7,250 | 4,400 | 7,350 | 4,800 | 2,500 | 2,600 | 3,700 | 650 | 2,450 | 2,250 | 1,050 | 6,700 | 1,400 |
| Globigerina bulloides | 17 | 21 | 25 | 16 | 25 | 14 | 21 | 18 | 17 | 16 | 18 | 19 | 24 | 23 | 20 | 13 | 16 | 17 | 11 | 12 | 17 | 9 | 11 | 8 | 10 | 6 | 5 | 6 | 10 | 8 |
| G. digitata | | | | | | | | | .5 | | | | .3 | | .2 | | | | | | | .6 | | 1 | | | .4 | | | .6 |
| G. eggeri | 5 | 19 | 24 | 13 | 15 | 8 | 16 | 30 | 25 | 22 | 10 | 8 | 22 | 29 | 19 | 36 | 13 | 27 | 15 | 10 | 13 | 30 | 39 | 19 | 18 | 19 | 15 | 32 | 29 | 41 |
| G. hexagona | | | | | .2 | | .4 | | | | .5 | | | | | | | | | .2 | | | | | | | | | | |
| G. inflata | 8 | 23 | 25 | 29 | 16 | 18 | 17 | 17 | 24 | 16 | 24 | 22 | 19 | 12 | 19 | 22 | 23 | 22 | 28 | 17 | 14 | 25 | 22 | 23 | 34 | 23 | 29 | 42 | 43 | 10 |
| G pachyderma | | .6 | .5 | 1 | .2 | | | 1 | 2 | 1 | | | | 1 | | 4 | 2 | 1 | .4 | .7 | 2 | 4 | 3 | 2 | 4 | 2 | 2 | 9 | 6 | 6 |
| G. quinqueloba | | | | | | | | | | | | | .3 | | .5 | | | | | | | | | 1 | .6 | .6 | | | | |
| Globigerinella aequilateralis | 2 | 2 | 3 | 2 | 2 | 2 | 1 | | .3 | 1 | 1 | 2 | 1 | .5 | 2 | .3 | 1 | .7 | 2 | 3 | 3 | | | 2 | .6 | 1 | | .4 | .2 | |
| Globigerinita glutinata | 4 | 1 | 4 | 2 | 5 | 5 | 2 | .7 | 3 | 4 | 2 | 3 | .5 | .5 | 2 | .3 | 1 | .7 | 1 | 2 | 1 | .6 | | .4 | | 1 | .4 | .4 | | 1 |
| Globigerinoides conglobata | .3 | | | | .3 | | .2 | | | | | | | | | .3 | .3 | .2 | | .2 | .3 | | | | | | .4 | | | .3 |
| G. rubra | 36 | 17 | 9 | 16 | 21 | 30 | 29 | 24 | 18 | 15 | 20 | 22 | 18 | 19 | 18 | 13 | 20 | 16 | 31 | 31 | 29 | 14 | 9 | 27 | 16 | 20 | 26 | 4 | 5 | 13 |
| G. sacculifera | 15 | 2 | 2 | 5 | 1 | 4 | 2 | .3 | .8 | 7 | 6 | 4 | 1 | .3 | 2 | | | 3 | .4 | 1 | 1 | .3 | .6 | 4 | 5 | 3 | 5 | 2 | | |
| Globorotalia hirsuta | 2 | .3 | .5 | 2 | 2 | 1 | 1 | .7 | 1 | .5 | .3 | R | .3 | .3 | 2 | 1 | 1 | | | | | | .6 | R | 3 | 4 | | | | |
| G. menardii | .2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. menardii - tumida group | | | | | | R | .2 | | | | R | R | | .3 | | | | .8 | | 1 | 3 | .3 | | .4 | | 1 | 4 | | | .3 |
| G. punctulata | .7 | | | 3 | .7 | 2 | 1 | | | .5 | 2 | 1 | | 2 | | 2 | 1 | .2 | 4 | 2 | | 2 | 2 | 1 | .3 | | 1 | .4 | | 3 |
| G. scitula | .5 | 1 | 2 | .4 | 1 | 1 | 1 | .7 | .3 | | .8 | 2 | .5 | 1 | 1 | | .6 | .2 | | .2 | .3 | .6 | | .4 | | .3 | | | .7 | |
| G. truncatulinoides | 7 | 11 | 3 | 6 | 10 | 12 | 5 | 7 | 8 | 17 | 13 | 13 | 12 | 10 | 11 | 7 | 16 | 9 | 7 | 19 | 15 | 13 | 12 | 12 | 8 | 16 | 9 | 4 | 5 | 15 |
| Orbulina universa | 2 | 3 | 3 | 3 | .8 | 1 | 2 | 1 | 2 | | 1 | 2 | .8 | 1 | 3 | .7 | 4 | 1 | .4 | 2 | .7 | .6 | .6 | 1 | 2 | .6 | 2 | | 1 | .6 |
| Pulleniatina obliquiloculata | 1 | | | .4 | | 2 | .2 | | | | | | | | | | | .2 | | | | .3 | | | | .3 | .4 | | | |
| [Sphaeroidina bulloides] | | .3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sphaeroidinella dehiscens | .2 | | | | | | | | | | .3 | | | | .2 | | | | | | .3 | | | | | .6 | | | | |
| BENTHONIC POPULATION | 35 | 50 | 150 | 120 | 200 | 100 | 80 | 85 | 140 | 50 | 120 | 70 | 70 | 33 | 125 | 210 | 110 | 80 | 115 | 33 | 50 | 110 | 175 | 75 | 20 | 60 | 40 | 100 | 125 | 60 |
| Anomalina sp | | | | | .5 | 1 | | | | 2 | | | | | 2 | | | | | | | | | | | | 2 | | | |
| Bolivina pseudoplicata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .8 | |
| Bulimina aculeata | | | | | .5 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cassidulina crassa | | | | | .5 | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. subglobosa | 3 | 2 | .7 | 6 | 6 | 2 | | 5 | .7 | | 3 | 3 | 2 | 3 | 5 | 3 | 8 | 10 | 1 | 6 | 2 | 3 | 3 | 1 | | | 5 | | 2 | 5 |
| Chilostomella oolina | | | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cibicides robertsonianus | 3 | | 4 | 6 | 4 | 3 | 4 | 3 | 2 | 14 | 3 | 11 | 5 | 3 | .8 | 1 | 4 | 1 | | | 2 | 6 | 3 | 4 | | 4 | | 2 | | 2 |
| C. sp. | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Ehrenbergina undulata | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eponides tumidulus | 3 | | .7 | | | | | | .7 | | 1 | 1 | | | .8 | | | | | | | | | 1 | | | 5 | | | |
| E. umbonatus and variants | 3 | 8 | 6 | 9 | 3 | 9 | 1 | 13 | 14 | 2 | 3 | 3 | 7 | 6 | 3 | 7 | 7 | 7 | 5 | 6 | 9 | 15 | 5 | 18 | 17 | 10 | 24 | 23 | 10 | |
| Glomospira cf. gordialis | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | |
| Gyroidina lamarckiana | 8 | | | | 1 | | 1 | | | | 1 | | 5 | | 2 | .5 | | 2 | | | | | | 1 | | 2 | | | | 2 |
| G. orbicularis | | | | | .5 | | | | | | | | | | | .5 | | | 1 | | | | | | | | | | | |
| G. soldanii variant | | | | | | 3 | | | | | | 1 | 3 | | 2 | | | | | | | | | | | 2 | | | | |
| Eggerella bradyi | 10 | 4 | 5 | 10 | 9 | 10 | 3 | 6 | 6 | 6 | 20 | 7 | 9 | 15 | 12 | 3 | 7 | 18 | 9 | 6 | 6 | 5 | 2 | 21 | 6 | 10 | 5 | 5 | 6 | 9 |
| Nonion barleeanum | | | | | .5 | | | | | | | | | | | | | | | | | | | | | | | | | |
| N. formosum | 3 | 2 | 1 | 1 | 1 | 1 | 3 | | | | 2 | | | 3 | .8 | .5 | 1 | 4 | | | | | | | 6 | 3 | | | | 2 |
| N. germanicum | | | | | | | | | | | | | | | | | | | 1 | 3 | | | | | | | | | | |
| N. pompilioides | | 2 | 4 | 2 | 1 | 6 | 3 | | | 2 | | 8 | 3 | 3 | 4 | 1 | | 2 | 1 | | 2 | | | | | | 5 | 4 | 2 | 3 |
| Planulina wuellerstorfi | 8 | 11 | 5 | 4 | 4 | 10 | 32 | 6 | 6 | 6 | 11 | 15 | 8 | | 10 | 1 | 6 | 6 | 2 | 18 | 13 | 10 | 2 | 7 | 28 | 8 | 13 | 8 | 8 | 5 |
| Plectina apicularis | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| **Epistominella exigua** | 3 | 11 | 10 | 19 | 13 | 12 | 19 | 27 | 23 | 22 | 11 | 9 | 12 | 6 | 11 | 20 | 19 | 11 | 13 | 6 | 6 | 27 | 16 | 23 | 17 | 14 | 7 | 15 | 30 | 23 |
| E. umbonifera | 8 | 30 | 33 | 25 | 19 | 19 | 6 | 25 | 27 | 28 | 17 | 9 | 17 | 33 | 32 | 40 | 27 | 6 | 20 | 27 | 33 | 15 | 52 | 11 | 22 | 24 | 22 | 22 | 12 | 35 |
| Pullenia bulloides | 3 | 9 | 8 | 7 | 6 | 13 | 11 | 7 | 8 | 4 | 6 | 7 | 6 | | 5 | 7 | 11 | 9 | 36 | 15 | 13 | 4 | 6 | 10 | | 10 | 5 | 5 | 13 | 5 |
| P. quinqueloba | 3 | 4 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | | 3 | | .8 | 1 | | 1 | 3 | | | | .6 | | | | | | | |
| P. sp. | 3 | | .7 | 1 | 3 | | 3 | | 1 | | | 1 | 3 | | | .5 | 1 | | | | | 1 | | | | | | | .8 | |
| Pyrgo murrhina | | 4 | 5 | 3 | 3 | 3 | 4 | 2 | 8 | | 3 | 4 | 9 | 6 | 2 | 4 | 6 | 2 | 3 | | | 2 | 2 | | | | | | 5 | |
| P. oblonga | | | | 1 | .5 | 1 | 6 | | | | | | | | | 2 | | | | | | | | | | | | | | |
| Quinqueloculina venusta | | 4 | .7 | 1 | .5 | 2 | | 2 | 1 | 4 | | 3 | | | 3 | 3 | 2 | 2 | | 6 | 2 | 5 | 2 | | | | | | 2 | 3 |
| Q. cf. weaveri | | 2 | | | .5 | 2 | 1 | | | 2 | | 1 | | | | | 1 | | | | | 1 | | | | | | | | |
| Robulus | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .8 | 2 |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 2 | .7 | 2 | 1 | | | | .7 | | 2 | 3 | | 3 | .8 | 1 | 1 | | | 3 | | 1 | 2 | | | | | 1 | 2 | |
| Spiroloculina sp. | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | |
| Textularia australis | 5 | | | | | | | | | 4 | 12 | 9 | 6 | 6 | 2 | 1 | 8 | 16 | 7 | 3 | 6 | 2 | 4 | 1 | | 2 | 5 | | 2 | 3 |
| Uvigerina hollicki | | | | | 15 | 2 | 1 | 1 | | | 5 | | 5 | | 2 | | | | | | | | | | | | | | | |
| U. hollicki variant | | | | | | | | | | | | | | | | | | | | | 4 | 5 | 1 | 1 | 6 | 12 | | 3 | 2 | 2 |
| Valvulineria humilis | 21 | 4 | 9 | 3 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina advena | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | |
| V. bradyi | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| V. complanata | | | | | | | | | | | | | | | | .5 | | | | | | | | | | | | | | |

of turbidity currents. It is belived that displacement of sediment has not seriously disturbed this core and that it may be satisfactory for purposes of possible chronology.

The upper fauna seems to be a normal mid-latitude assemblage. At 39.5 cm. an apparently colder water fauna is suggested by the presence of *Globigerina pachyderma*, the increase in *G. inflata* and dropping out of *Globorotalia menardii-tumida* and *Pulleniatina obliquiloculata*. *P. obliquiloculata* is present at 139.5—140 cm. and also *Globorotalia hirsuta*, suggesting slightly warmer surface temperatures, but not so warm as the modern. At 189.5—190 cm. *Globorotalia menardii-tumida* is present along with *Pulleniatina obliquiloculata* and *Globigerina pachyderma* is absent; this indicates probable return to modern conditions. This fauna extends to near

259.5—260 cm. where another colder water assemblage is suggested by the absence of the warm-water species and the presence of *Globigerina pachyderma*; an increase of *G. eggeri* in this fauna cannot be explained. At 319.5—320 cm. the presence of *Globorotalia menardii-tumida* indicates slightly warmer conditions, and at 329.5—330 cm. typical mid-latitude conditions are indicated which continue to 459.5—460 cm., with slight variations.

Presence of *Globigerina pachyderma* at 469.5—470 cm. and absence of *Globorotalia menardii-tumida* suggest colder conditions extending to approximately 500 cm. The mid-latitude fauna appears at 519.5—520 cm. There are three additional, lower apparent shifts to colder water assemblages, at 619.5—620 cm., 649.5—650 cm., and 740—780 cm. The bottom fauna at 789.5—790 cm. suggests a possible trend to warmer water by the presence of *Globorotalia menardii-tumida* and the relative abundance of *G. truncatulinoides*.

**Core 221.** This core contains a mixed benthonic fauna of shallow- and deep-water species in most of the samples. The shallow-water species which are clearly displaced from shoaler water are as follows:

*Anomalina balthica*
*Bolivina pseudoplicata*
*B. subaenariensis*
*B.* sp. 1
*Bulimina exilis*
*B. marginata*
*B. mexicana*
*B.* aff. *subacuminata*
*Cancris* cf. *oblonga*
*Cassidulinoides mexicana*
*Discorbis mamilla*
*Elphidium advenum*
*E. complanatum*
*E. crispum*
*Nonion asterizans*
*Planorbulina mediterranensis*
»*Rotalia*» *beccarii* variants
*Uvigerina senticosa*
*Virgulina mexicana*

The following species are probably displaced, but are somewhat questionable:

*Bulimina aculeata*
*Cibicides lobatulus*
*Discorbis williamsoni*
*Rotamorphina laevigata*

Some of these shallow-water species appear to be restricted normally to a depth less than approximately 100 m. This suggests that the sediment in which they are enclosed moved downslope from a depth not greater than approximately 100 m. Since they are mixed with typical deep-water benthonic species, they must have been deposited at the approximate depth where they now occur. The sediment containing this mixed fauna also contains abundant sand in the majority of samples and numerous shell fragments in many samples. Examination of the core shows that the top section is very sandy to 115.5 cm. Below that depth there are numerous sand partings and »lenses» of sand. At 535 cm. an almost pure quartz sand occurs and extends to the bottom of the core. All the samples examined for Foraminifera contained some to abundant sand. Many of the quartz grains were larger than 1 mm. in diameter and some were well-rounded and frosted. This suggests that the sediment originated at or near the turbulent surf zone.

A few of the samples in this core did not contain any shallow-water benthonic species, and in some other samples these species were rare, as in samples 13—17 and 43—47. These samples all contain several quartz grains and it is believed that they represent displaced material. The occurrence of occasional specimens of shallow-water species in some of these samples suggests that they would have been found in all samples in the mid-section if sufficient material were examined.

Core 221 is interpreted as containing two

TABLE 4. Occurrences of Foraminifera in selected samples from Core 221 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 221 | DEPTH- 4,940M. | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 2 | 6 | 7 | 8 | 9 | 10 | 13 | 18 | 23 | 28 | 33 | 38 | 43 | 48 | 54 | 55 | 56 | 57 |
| CM. FROM TOP OF CORE | 1.5-2 | 9.5-10 | 49.5-50 | 59.5-60 | 69.5-70 | 79.5-80 | 89.5-90 | 119.5-120 | 169.5-170 | 219.5-220 | 269.5-270 | 319.5-320 | 369.5-370 | 419.5-420 | 469.5-470 | 529.5-530 | 539.5-540 | 549.5-550 | 559.5-560 |
| PLANKTONIC POPULATION | 31 700 | 27 700 | 14 500 | 11 000 | 4 450 | | 6 500 | 16 200 | 28 000 | 63 500 | 25 700 | 51 200 | 59 000 | 36 000 | 25 500 | 26 500 | 3 350 | 70 000 | 2 500 |
| Globigerina bulloides | 19 | 3 | 16 | 16 | 23 | | 41 | 5 | 5 | 5 | 1 | 4 | 3 | 3 | 5 | 5 | 27 | 67 | 47 |
| G. digitata | | .2 | .3 | | | | | | | | | | | | | | | | |
| G. eggeri | 18 | 4 | 8 | 12 | 12 | | 13 | 9 | 15 | 13 | 6 | 8 | 11 | 9 | 12 | 5 | 23 | 2 | 29 |
| G hexagona | | | | | | | 3 | 1 | .3 | | | 1 | 3 | 1 | 1 | 2 | | | |
| G. inflata | 25 | 14 | 20 | 20 | 33 | | 21 | 24 | 10 | 8 | 14 | 15 | 14 | 23 | 14 | 18 | 17 | 3 | |
| G. pachyderma | .5 | | .8 | 2 | .5 | | 3 | .3 | | | | | | 8 | | .5 | 4 | 1 | 7 |
| G. quinqueloba | | .2 | | .4 | | | .3 | | .7 | | | | | | | | .7 | 1 | 1 |
| Globigerinella aequilateralis | | 2 | 2 | 2 | 2 | | 1 | .3 | 1 | .6 | .7 | 2 | 1 | 1 | .3 | 1 | 1 | 4 | |
| Globigerinita glutinata | 2 | 1 | 2 | 7 | 2 | | 2 | 1 | 2 | 5 | | 2 | 2 | 5 | 4 | 9 | 6 | 2 | 3 |
| Globigerinoides conglobata | .3 | .5 | .3 | .2 | | | | .6 | 2 | | .4 | .5 | 1 | .8 | .8 | .5 | .4 | R | |
| G rubra | 12 | 18 | 9 | 7 | 9 | | 6 | 31 | 17 | 30 | 17 | 25 | 19 | 20 | 21 | 17 | 10 | 9 | 10 |
| G sacculifera | 12 | 36 | 17 | 7 | 8 | | 5 | 15 | 21 | 16 | 19 | 19 | 22 | 16 | 21 | 19 | 3 | 3 | 1 |
| Globorotalia hirsuta | | .2 | .5 | | 2 | | | .6 | | .6 | 1 | .5 | .2 | .5 | .5 | | .7 | R | |
| G menardii | 1 | 10 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → | |
| G. menardii-tumida group | | | .5 | | 1 | | .3 | 4 | 13 | 10 | 20 | 11 | 9 | 9 | 9 | 9 | 1 | R | |
| G. punctulata | | .2 | | | | | | .3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | .5 | .7 | R | |
| G. scitula | .3 | | | | | | | | | | | | | | | | | | .6 |
| G. truncatulinoides | 8 | 7 | 19 | 18 | 3 | | 3 | 6 | 9 | 8 | 17 | 5 | 8 | 7 | 8 | 10 | 3 | .5 | 2 |
| G. tumida | .3 | 3 | — | — | — | — | → | | | | | | | | | | | | |
| Orbulina universa | .5 | 1 | 4 | 8 | 5 | | .3 | | 1 | .6 | 2 | 3 | 1 | .3 | .3 | 2 | 1 | 6 | |
| Pulleniatina obliquiloculata | .3 | .2 | .3 | | | | | .6 | 3 | .3 | 1 | 1 | 2 | .3 | 1 | .5 | | | |
| [Sphaeroidina bulloides] | | | | | | | | | | .3 | | | | | | | | | |
| BENTHONIC POPULATION | 650 | 60 | 100 | 40 | 300 | 95 | 250 | 25 | 25 | 20 | 30 | 60 | 50 | 50 | 50 | 25 | 65 | 1050 | 50 |
| Anomalina balthica | 2 | 2 | | | | 1 | 2 | | | | | | | | | | | | |
| Bolivina petterssoni | 1 | 12 | 15 | 8 | 7 | 13 | 5 | 4 | 8 | 6 | 10 | 3 | .6 | 2 | 8 | 4 | 22 | 50 | |
| B pseudoplicata | .2 | | 1 | | 1 | 1 | | | | | | | | | | | | | |
| B. pseudopunctata | | | | | | 1 | | | | | | | | | | | | | |
| B. sp. 1 | 1 | | 1 | | .7 | | 2 | | | | | | | | | | | | |
| B. subaenariensis | 1 | | 2 | | | 1 | 2 | | | | | | | | | | | .8 | |
| Bulimina aculeata | 2 | | | | | | .8 | | | | | | | | | | | .1 | |
| B. exilis | | | 1 | | | 1 | | | | | | | | | | | 2 | 3 | 2 |
| B. marginata variant | | | | | 1 | | | | | | | | | | | | | 2 | |
| B. mexicana | .5 | | | | | | | | | | | | | | | | | | |
| B. aff. subacuminata | | | | | | | | | | | | | | | | | | .7 | |
| Cancris cf. oblonga | | | | | | | | | | | | | | | | | | .4 | |
| Cassidulina carinata | 4 | | 4 | 3 | 4 | 3 | .8 | | | | | | | | | | 3 | 2 | 6 |
| C crassa | | | | | | | .8 | | | | | | | | | | | .2 | |
| C. subglobosa | .6 | 5 | | | | 2 | | | | | 3 | | | | | | | | |
| Cassidulinoides mexicana | | | | | | | | | | | | | | | | | | 2 | |
| Chilostomella oolina | | | 1 | | | 1 | | | | | | | | | | | | | |
| Cibicides lobatulus | 15 | | | 3 | 9 | 5 | 14 | | | | | | | | | | 16 | .4 | 26 |
| C. sp. | | | | | | | | | | | | | | | | | | .8 | |
| C. robertsonianus | .3 | 2 | 3 | 3 | | 2 | | 4 | 12 | 13 | 3 | 10 | 8 | 4 | 4 | | | | |
| Cibicidina rhodiensis | .6 | | | | | | | | | | | | | | | | | .4 | |
| Discorbis mamilla | 1 | | | | 2 | 2 | 4 | | | | | | | | | | | .2 | 2 |
| D. williamsoni | 1 | 2 | | | 2 | 1 | 2 | | | | | | | | | | 2 | .5 | 2 |
| Elphidium advenum | 17 | 3 | 7 | 3 | 23 | 13 | 24 | | | | 7 | | 2 | | | | 6 | 7 | 20 |
| E. complanatum | 17 | 3 | 2 | 3 | 21 | 8 | 23 | | | | 2 | | | | 2 | | 18 | .8 | 16 |
| E. crispum | 5 | | | 3 | 6 | 2 | 4 | | 4 | | | | | | | | 5 | | 2 |
| Eponides tumidulus | | | | | | | | | | | | 3 | | | | 4 | | | |
| E. umbonatus and variants | 1 | 7 | 11 | 11 | .7 | 6 | .8 | 8 | 8 | 6 | 10 | 5 | 6 | 11 | 8 | 4 | 2 | .3 | |
| Globobulimina cf. turgida | | | | | | 3 | | | | | | | | | | | 2 | 2 | |
| Gyroidina lamarckiana | | 7 | 5 | 8 | | | | | | 6 | | 3 | 4 | | | | | .3 | |
| G. orbicularis | | | | | | | | | | | | 2 | | | | | | | |
| G. soldanii variant | | | | 3 | | | | | | | | 10 | | 4 | 6 | 4 | | | |
| Eggerella bradyi | .3 | 5 | | | | 1 | | 16 | | | 3 | 3 | 6 | 7 | 4 | 8 | | .3 | |
| Nonion asterizans | 1 | | | | .2 | | .8 | | | | | | | | 2 | | 3 | .4 | |
| N. barleeanum | 1 | | | | | 2 | | | | | | | | | | | | .1 | 2 |
| N. formosum | | | 1 | | | | | | | | 3 | 3 | 4 | 4 | 4 | 8 | | | |
| N. pompilioides | .8 | | | | .7 | 1 | .8 | 8 | 4 | | 7 | 10 | 6 | 4 | 2 | 8 | 2 | .7 | |
| Nummoloculina irregularis | | | | | | | | | | | | | | | | | | .1 | |
| Osangularia cultur | | | | | | 1 | | | | | | | | | | | | | |
| Patellina corrugata | | | | | .7 | | | | | | | | | | | | | | |
| Planorbulina mediterranensis | 8 | 2 | 1 | 3 | 4 | | 4 | | | | | | | | | | 2 | 17 | 12 |
| Planulina wuellerstorfi | 3 | 13 | 1 | 8 | .7 | 4 | 2 | | 4 | 6 | 7 | 13 | 8 | 9 | 2 | 4 | 2 | | 4 |
| Plectina apicularis | | 3 | | | | | | | | | | | | | | | | | |
| Epistominella exigua | .3 | | 2 | 3 | | 4 | 2 | 4 | 4 | | 10 | 2 | | 2 | 10 | 4 | | 1 | 2 |
| E. umbonifera | 3 | 23 | 23 | 26 | .7 | 6 | | 16 | 12 | 19 | 10 | 11 | 17 | 11 | 20 | 31 | | .1 | |
| Pullenia bulloides | .5 | 7 | 4 | 5 | | 3 | .8 | 4 | 12 | 6 | 7 | 13 | 6 | 20 | 16 | 12 | | .7 | 2 |
| P. quinqueloba | | | 1 | | .7 | 1 | | | 4 | | 3 | | 2 | | 4 | | | .5 | |
| P sp. | | | 2 | 3 | | | | | 8 | | 3 | | | | | 4 | | .2 | |
| Pyrgo murrhina | .5 | 2 | 2 | | 1 | 2 | | 12 | 4 | | | 3 | 6 | 11 | 4 | | | 2 | |
| P. oblonga | .3 | | | | | | | 8 | 4 | | | | | 4 | 2 | | | | |
| Rotamorphina laevigata | | | 1 | | | | | | | | | 2 | | | | | | .1 | |
| Quinqueloculina venusta | | | | | | | | | | | | 2 | 6 | | | | | | |
| Q cf weaveri | .8 | | | | | | | 12 | 8 | | | | | 2 | | | | | |
| Robertina bradyi | | | | | | | | | | | | | | | | | | .2 | |
| "Rotalia" beccarii variant | 5 | | | | .7 | | 4 | | | 6 | | | 2 | | | | 5 | | |
| "R." beccarii sobrina | 2 | | | | .7 | | | | | | | | | | | | | | 4 |
| Sigmoilina schlumbergeri | .2 | | | | | | | | | | | | | | | | | | |
| S tenuis | .2 | | | | | | | | | 6 | | | | | 2 | | | | |
| Siphotextularia curta | | | | | | | | | | | | | | 2 | | | | | |
| S. rolshauseni | | | 1 | | | | | 4 | 4 | 6 | 7 | | 2 | | | | | .3 | |
| Uvigerina hollicki | | | | 3 | 1 | 5 | .8 | | | 6 | 3 | 2 | 2 | | | 4 | 2 | | |
| U. hollicki variant | 4 | | 1 | | | | | | | 13 | | | | | | | | | |
| U senticosa | | | | | | | | | | | | | | | | | | 1 | |
| Virgulina advena | | | | | | | | | | | | | | | | 4 | | .2 | |
| V bradyi | .2 | 2 | | | 2 | | .8 | | | | | | | | | | 2 | .1 | |
| V. complanata | .2 | | | | | | | | | | | | | | | | | | |
| V mexicana | | | | 5 | | 1 | | | | | | | 4 | 2 | | | | 1 | |
| Miliolids | .8 | | | | 2 | | | | | | | | | | | | 2 | .3 | |

principal displacements from shoal water, one extending from somewhat deeper than the bottom of the core up to approximately 540 cm. beneath the surface and the bottom of the other at about 120 cm. The relative abundance of shoal-water specimens in these two sections of the core and the presence of sand both suggest this. The midsection, between about 120 cm. and 530 cm., is believed to represent the finer-sediment fraction from a turbidity current which deposited the lower material; or it may represent finer fraction from other, nearby turbidity currents.

**Core 223.** There is no faunal evidence that any of the sediment in this core has been displaced from a shoaler depth. It appears to be a relatively uniform, lime-rich sediment with a few sand particles. It is believed that this core may be useful for interpretation of chronology.

The upper fauna is a normal mid-latitude assemblage with some mixture of low-latitude species extending to 39.5—40 cm. At 49.5—50 cm. there is an absence of *Globorotalia menardii-tumida* which may indicate that a slight shift of low-latitude water masses carrying this population have shifted southward. Essentially the modern fauna is present from 69.5 cm. to 109.5 cm., and at 119.5—150 cm. there is an apparent change in the fauna suggesting slightly cooler-than-present surface temperatures. This is suggested by a lower frequency of *Globigerina inflata*, increased abundance of *G. bulloides*, absence of *Globorotalia menardii-tumida*, and generally lower percentage of *G. truncatulinoides*; *Globigerina pachyderma* also is present in numerous samples in this section. At 429.5—430 cm. the *Globorotalia menardii-tumida* group is present, there is a slight increase in frequency of *G. truncatulinoides*, *Pulleniatina obliquiloculata* is present in some samples, *Globigerina inflata* shows a slightly higher frequency trend and there is a higher frequency of *Globigerinoides sacculifera*. This

TABLE 5. Occurrences of Foraminifera in selected samples from Core 223 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 223 DEPTH - 3,820 M. | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 6 | 8 | 13 | 18 | 23 | 29 | 34 | 39 | 44 | 49 | 51 | 55 | 59 | 61 | 66 | 71 | 76 | 79 | 80 |
| CM. FROM TOP OF CORE | 3.5-4 | 39.5-40 | 49.5-50 | 69.5-70 | 119.5-120 | 169.5-170 | 219.5-220 | 279.5-280 | 329.5-330 | 379.5-380 | 429.5-430 | 479.5-480 | 499.5-500 | 539.5-540 | 579.5-580 | 599.5-600 | 649.5-650 | 699.5-700 | 749.5-750 | 779.5-780 | 789.5-790 |
| PLANKTONIC POPULATION | 37,300 | 24,000 | 28,200 | 28,400 | 27,000 | 35,300 | 37,800 | 11,500 | 13,300 | 28,200 | 14,000 | 18,600 | 7,800 | 15,900 | 10,100 | 21,300 | 19,600 | 8,650 | 5,850 | 5,850 | 2,300 |
| Globigerina bulloides | 14 | 37 | 38 | 47 | 44 | 51 | 48 | 36 | 29 | 39 | 33 | 45 | 31 | 24 | 31 | 34 | 34 | 24 | 18 | 25 | 24 |
| G. eggeri | 21 | 18 | 23 | 30 | 30 | 22 | 17 | 35 | 46 | 18 | 19 | 14 | 26 | 28 | 11 | 29 | 25 | 39 | 44 | 31 | 50 |
| G hexagona | | | | | | | | | | 1 | | | | 2 | .3 | 1 | | | 2 | .8 | |
| G inflata | 32 | 18 | 24 | 11 | 15 | 15 | 27 | 13 | 18 | 25 | 24 | 22 | 30 | 24 | 43 | 25 | 23 | 28 | 24 | 21 | 14 |
| G pachyderma | | | | | | .2 | | | .5 | .2 | | .3 | | | | | .3 | 2 | 1 | .8 | 1 |
| G quinqueloba | | | .7 | | | | | | | | | | | | | | | | | | |
| G sp. 1 | | | | | | | | | | | | | | | | | | | 1 | | |
| G. sp 2 | | | | | | | .2 | .6 | | | | | | | | | | | | | 2 |
| Globigerinella aequilateralis | .7 | 1 | .5 | .5 | .2 | .5 | .5 | 2 | .5 | 2 | 2 | 1 | .4 | | 1 | .3 | 1 | | | .5 | .7 |
| Globigerinita glutinata | .2 | 1 | 1 | .5 | .2 | .5 | 5 | .8 | .2 | .7 | | .3 | .4 | 1 | 2 | 1 | 1 | 1 | .6 | .5 | .7 |
| Globigerinoides conglobata | | .1 | | | | | | | | | .5 | | | | .3 | | | | | | |
| G. rubra | 13 | 10 | 4 | 5 | 4 | 5 | 2 | 6 | 3 | 8 | 14 | 7 | 5 | 8 | 5 | 6 | 9 | 4 | 5 | 6 | 3 |
| G sacculifera | 8 | 5 | 2 | 2 | 2 | 5 | 2 | 1 | 1 | 1 | 2 | 2 | 3 | 5 | 2 | 1 | 2 | | | 1 | .7 |
| Globorotalia hirsuta | | | | | | .2 | | | | | | | | | | | | | | | |
| G. menardii | 4 → | | | | | | | | | | | | | | → | | | | | | |
| G. menardii-tumida group | | 1 | | .4 | | | | | | | 1 | 2 | .4 | 2 | 1 | | | | | | |
| G punctulata | .7 | .1 | | | .2 | | | .3 | .5 | 1 | .5 | .3 | .4 | 1 | .6 | | .7 | .4 | | .3 | |
| G scitula | .7 | 1 | .2 | .2 | .2 | .4 | 2 | .6 | .5 | .2 | | | | .8 | .6 | .3 | 3 | | .6 | .5 | |
| G. truncatulinoides | 3 | 3 | 2 | 1 | | | .3 | .3 | .7 | .7 | 1 | 2 | .4 | .8 | .6 | | .3 | | .6 | 12 | 3 |
| G. tumida | .5 → | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | 2 | 3 | 3 | 2 | 4 | 2 | 1 | 5 | .5 | 3 | 3 | 5 | 3 | 2 | 2 | 2 | 2 | .7 | 4 | .8 | .3 |
| Pulleniatina obliquiloculata | .2 | | | | | | | | | | | | | .8 | | | | | | | |
| BENTHONIC POPULATION | 70 | 70 | 90 | 50 | 95 | 90 | 90 | 50 | 120 | 125 | 80 | 70 | 100 | 50 | 60 | 65 | 80 | 70 | 55 | 30 | 20 |
| Anomalina sp | | 1 | 1 | | | | | | | | 1 | 1 | | | | | | 1 | | | 4 |
| Bolivina pseudopunctata | | | | | 3 | 1 | | 2 | | 4 | 1 | 3 | | | | | | | | | |
| Bulimina aculeata | | | | | | | | | | | | | | | | | | 1 | | | |
| B. alazanensis | | 1 | | | | | | | | | | | | | | | | | | | |
| Cassidulina carinata | | | 1 | | | | | | | | | | | | | | | 1 | | | |
| C. subglobosa | | | 2 | 2 | | 1 | | 2 | .8 | | 6 | | 1 | 4 | | | | | | | |
| Chilostomella oolina | | | | 2 | | | | | | | | | | | | | | | | | |
| Cibicides robertsonianus | 18 | 1 | 9 | | 5 | 1 | 6 | | .8 | 2 | 1 | 6 | 3 | 24 | 9 | 5 | 5 | 1 | 9 | | |
| C. sp. | | 6 | 8 | | | 1 | 7 | 2 | | 2 | 4 | | | | 2 | | | | | 3 | |
| Ehrenbergina undulata | | | | | 1 | 1 | | | | .8 | | | | | | | | | | | |
| Eponides polius | | | | | | | | | | | | | | | | | 2 | | | | |
| E. umbonatus | 14 | 1 | 3 | 10 | 8 | 4 | 5 | 8 | 10 | 7 | 4 | 3 | 9 | 12 | 5 | 3 | 5 | 8 | 4 | 7 | 4 |
| Globobulimina cf. turgida | | | | | | | | | | | | | | | 2 | | | | | | |
| Gyroidina lamarckiana | | | | | 1 | | 2 | | .8 | 2 | 1 | 3 | 1 | 4 | | 1 | 2 | | 2 | 7 | |
| G orbicularis | 4 | | | | | | | | | | | | | 2 | 2 | | | | | | |
| G soldanii variant | | 3 | 10 | 4 | | 4 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | | 5 | 3 | 4 | 7 | | | |
| Hoglundina elegans | 6 | 20 | 8 | 2 | | | | | | .8 | | | | 2 | | | | | | | |
| Eggerella bradyi | | | 1 | 12 | 4 | 12 | | 6 | .8 | 10 | 2 | 3 | | | 5 | 5 | 1 | 1 | 5 | | |
| Laticarinina pauperata | | 3 | 3 | | | | | | | | | | | | | | | | | | |
| Nonion barleeanum | | | | | | | | | | .8 | 1 | 3 | 4 | | 9 | | 2 | | | | |
| N. formosum | | | | | | | 2 | 2 | | | 2 | | | | | | | | 4 | | 4 |
| N. germanicum | 3 | 6 | 1 | 2 | 1 | | | | 3 | .8 | | | | | | | | | | | |
| N. pompilioides | | | 1 | 2 | 7 | 9 | 7 | 4 | .8 | 7 | 4 | | 7 | | 11 | 5 | 6 | 6 | 5 | | 4 |
| Patellina corrugata | | | 1 | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 21 | 22 | 14 | 8 | 6 | 14 | 22 | 19 | 10 | 11 | 12 | 13 | 9 | 22 | 9 | 12 | 9 | 6 | 15 | 24 | 27 |
| Epistominella exigua | 18 | 7 | 14 | 37 | 25 | 12 | 10 | 17 | 16 | 20 | 16 | 26 | 14 | 8 | 18 | 20 | 38 | 29 | 31 | 21 | 22 |
| E. umbonifera | 7 | 8 | | | 1 | 7 | 15 | 2 | 4 | 3 | 2 | 6 | 5 | 2 | | | | 1 | 7 | 10 | 4 |
| Pullenia bulloides | | | 2 | 8 | 6 | 1 | 1 | 6 | 7 | 6 | 6 | 3 | 1 | 2 | | 6 | 4 | 6 | | 7 | |
| P quinqueloba | 3 | 3 | 1 | | | 7 | | | 2 | 2 | | 3 | 1 | 4 | | | 1 | 3 | 2 | | 14 |
| P. sp. | | | | | | 3 | | | .8 | | 1 | 4 | 4 | | 2 | | 2 | | | | |
| Pyrgo murrhina | 3 | 7 | 8 | 2 | 14 | 9 | 14 | 10 | 6 | 7 | 20 | 7 | 6 | 6 | 2 | 3 | 6 | | 11 | 10 | 4 |
| P. oblonga | | | | | | 3 | | 2 | | 3 | | 1 | | 2 | 2 | 1 | | | | | |
| Quinqueloculina venusta | 3 | 3 | | 4 | 5 | | 2 | 4 | .8 | 4 | 1 | | 2 | 2 | | | 5 | | | 3 | 4 |
| Q. cf. weaveri | | 1 | 7 | | | | 2 | 2 | .8 | | | | | | 4 | 1 | | | 2 | | |
| Robertina bradyi | 1 | | 1 | | | | | | | | | | | | | | | | | | |
| Sigmoilina schlumbergeri | | | | | | | | | | | | | | 2 | 2 | | | | | | |
| S. tenuis | | | | | | | | | | 2 | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 3 | 1 | | 1 | 3 | | 2 | .8 | .8 | | | | | 2 | 1 | | | | 7 | |
| Spiroloculina sp. | | | | 2 | | | | | | | | 1 | | | | | | | | | |
| Uvigerina hollicki | | | | | 9 | 1 | | 6 | 30 | .8 | 10 | 10 | 33 | | 11 | 32 | 5 | 28 | 2 | | 4 |
| Virgulina advena | 1 | | | | | 3 | 1 | | .8 | | | | | | | | | | 2 | | |
| V. bradyi | | 1 | 1 | | | | 1 | 2 | | | | 1 | | | 2 | | | | | | |
| V. complanata | | 1 | | | 1 | | | 2 | | 2 | | | 1 | | | | | | | | |

assemblage is similar to the modern one and extends to about 590 cm. Below that depth the fauna seems to represent considerably cooler surface conditions as suggested by the relative abundance of *Globigerina pachyderma* and decrease or absence of usual low-latitude species. Near the bottom of the core the relative abundance of *Globorotalia truncatulinoides* suggests a swing to somewhat warmer conditions.

*Globigerina hexagona* is present in low frequencies in a few samples below 379.5 cm. Typical *Globorotalia tumida* does not extend below 40 cm., and typical *G. menardii* extends, in a few samples as deep as 580 cm.

**Core 228.** This core contains numerous layers of fine, clean sand and a mixture of sand and mud elsewhere. The upper 25 cm. is essentially pure sand. The lowermost sections appear to contain little sand.

A displaced benthonic fauna occurs in the upper 35 cm. of the core, as shown by the presence of the following benthonic species whose normal habitat is at much shoaler depths:

- *Bolivina pseudoplicata*
- *Bulimina marginata*
- *Cancris* cf. *oblonga*
- *Cibicides lobatulus*
- *Cornuspira planorbis*
- *Discorbis mamilla*
- *D. williamsoni*
- *Planorbulina mediterranensis*
- *Rectuvigerina* sp.
- *»Rotalia» translucens*

The following shallower-water benthonic species occur from 149.5—160 cm.:

- *Anomalina balthica*
- *Cancris* cf. *oblonga*
- *Cornuspira planorbis*
- *Discorbis williamsoni*
- *Elphidium advenum*
- *Planorbulina mediterranensis*
- *Rectuvigerina* sp.

At 229—229.5 cm. *Discorbis williamsoni* is present.

It appears probable that most of the material in this core has been displaced from a shoaler depth, much of it probably from the continental shelf. The lowermost section may be an ex-

BLE 6. Occurrences of Foraminifera in ected samples from Core 228 in percent total population. Planktonic and benthonic populations computed separately.

| CORE 228 DEPTH-4,280 M. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AMPLE | 1 | 3 | 4 | 5 | 10 | 14 | 16 | 17 | 24 | 27 | 32 | 36 | 42 |
| M FROM TOP OF CORE | 9.5-10 | 29.5-30 | 34.5-35 | 39.5-40 | 89.5-90 | 129.5-130 | 149.5-150 | 159.5-160 | 229-229.5 | 259.5-260 | 309.5-310 | 349.5-350 | 408-408.5 |
| LANKTONIC POPULATION | 2,700 | 16,900 | 4,100 | 2,700 | 8,300 | 6,150 | 6,600 | 7,800 | 1,150 | 3,300 | 3,900 | 1,000 | 880 |
| andeina nitida | | .4 | | | | | | | | | | | |
| lobigerina bulloides | 50 | 11 | 47 | 16 | 18 | 22 | 38 | 27 | 21 | 20 | 21 | 16 | 22 |
| . digitata | 1 | | | | .4 | | .5 | | | | | | |
| . eggeri | 5 | 16 | 21 | 38 | 45 | 23 | 10 | 22 | 30 | 39 | 41 | 46 | 32 |
| . hexagona | 1 | | .4 | | | | .5 | | | | | | 3 |
| . inflata | 2 | 3 | 4 | 10 | 12 | 16 | 3 | 21 | 19 | 22 | 18 | 19 | 14 |
| . pachyderma | | | | | 3 | .5 | | .4 | | 1 | 2 | 2 | 1 |
| . quinqueloba | 1 | | | | | | | | | | | | |
| lobigerinella aequilateralis | | 3 | .4 | 1 | | 3 | 2 | 2 | .3 | .5 | | | 1 |
| lobigerinita glutinata | 17 | 1 | 5 | | 2 | 4 | 9 | 2 | 3 | .5 | | | 1 |
| lobigerinoides conglobata | | .4 | | | | | | .4 | | .5 | .4 | | |
| . rubra | 8 | 36 | 12 | 14 | 11 | 13 | 13 | 14 | 15 | 9 | 11 | 9 | 18 |
| . sacculifera | 1 | 12 | 4 | 11 | 5 | 7 | | 5 | 7 | 5 | 2 | 3 | 4 |
| loborotalia menardii | 1 | 11 | .8 | | | | .5 | | | | | | |
| . tumida | | 2 | | | | | | | | | | | |
| . punctulata | | 1 | .8 | 4 | .8 | 2 | | .4 | .3 | 1 | .8 | .8 | 1 |
| . scitula | 10 | .8 | 3 | | 1 | 4 | 21 | 2 | 1 | | .4 | .8 | 4 |
| . truncatulinoides | | .8 | .8 | 2 | | .5 | | | 1 | | 1 | | |
| rbulina universa | 3 | 2 | | 5 | 1 | 4 | 3 | 5 | 2 | 1 | 2 | 3 | |
| ulleniatina obliquiloculata | | 1 | | .6 | | | | | | | | | R |
| phaeroidinella dehiscens | | | | | | | | | | | | | R |
| ENTHONIC POPULATION | 150 | 75 | 90 | 60 | 60 | 50 | 195 | 40 | 7 | 50 | 55 | 50 | 12 |
| nomalina balthica | | | | | | | 2 | | | | | | |
| olivina pseudoplicata | | | 18 | | | | | | | | | | |
| . pseudopunctata | 1 | | | | | | 2 | | | | 2 | | 8 |
| ulimina alozanensis | | | 2 | | | | | | | | | | |
| . marginata variant | 7 | | | | | | | | | | | | |
| ancris cf. oblonga | 2 | | | | | | 2 | | | | | | |
| ossidulina carinata | | | 12 | | | | 4 | | | | | | 8 |
| . crassa | 4 | | 8 | | | | 4 | | | | | | |
| . subglobosa | | 3 | 1 | | | | | | | | 2 | 2 | |
| hilostomella oolina | | | | | | | 18 | 2 | | | | | |
| ibicides lobatulus | 7 | | 3 | | | | | | | | | | |
| . robertsonianus | | 5 | | | 4 | 4 | | 16 | | 4 | 2 | 4 | |
| ornuspira planorbis | 1 | | | | | | 2 | | | | | | |
| iscorbis mamilla | | | 11 | | | | | | | | | | |
| . williamsoni | 7 | 3 | 12 | | | | 8 | | 14 | | | | |
| hrenbergina undulata | | | | | 2 | | | | | 2 | | | |
| lphidium advenum | | | | | | | 2 | | | | | | |
| ponides umbonatus and variants | | 9 | | 5 | 11 | 15 | | 15 | 29 | 8 | 11 | 10 | 25 |
| lomospira charoides | | | 1 | | | | | | | | | | |
| yroidina lamarckiana | 1 | | | | | | | | | | | | |
| . orbicularis | | 1 | | | | | | | | | | | |
| . soldanii variant | | 4 | 1 | 2 | | | | 2 | | 4 | | | |
| ggerella bradyi | | 3 | 2 | 4 | 2 | | | 2 | | 4 | 2 | 2 | |
| aticarinina pauperata | | | | | | | | | | | | | 8 |
| odosaria sps. | | | | | | | 3 | | | | | | |
| onion barleeanum | | | | | | | | | | | | | 8 |
| . formosum | | 5 | | 2 | 8 | 6 | | 2 | | 4 | | | |
| . germanicum | | 19 | 9 | 2 | 3 | | | 5 | | 4 | 4 | 4 | 8 |
| . pompilioides | | 3 | 2 | 15 | 3 | 9 | | 8 | | 10 | 13 | 12 | 8 |
| atellina corrugata | 1 | | | | | | | | | | | | |
| lanorbulina mediterranensis | 4 | | 1 | | | | 2 | | | | | | |
| lanulina wuellerstorfi | | 5 | 1 | 18 | 6 | 9 | | 5 | 29 | 17 | 14 | 6 | |
| pistominella exigua | 4 | 7 | | 9 | 16 | 13 | 6 | 8 | | 2 | 7 | 23 | 17 |
| . umbonifera | | 12 | 2 | 14 | 15 | 15 | | 10 | 14 | 10 | 13 | 4 | |
| ullenia bulloides | | 7 | 2 | 16 | 8 | 6 | 2 | 8 | 14 | 13 | 20 | 16 | |
| . quinqueloba | 5 | 5 | | 4 | 3 | 9 | 4 | 2 | | | 4 | 2 | |
| . sp. | 5 | 1 | | 2 | 5 | 2 | 6 | | | | | | |
| yrgo murrhina | | | | 5 | 2 | 2 | | 8 | | 8 | | 4 | |
| . oblonga | | | | | 2 | | | | | | | | |
| uinqueloculina venusta | | 3 | | | | | | | | 4 | 2 | 2 | |
| . cf. weaveri | | | | | | | | | | 2 | | | |
| ectuvigerina sp. | 5 | | | | | | 6 | 2 | | | | | |
| obulus | | 3 | | | 2 | | | | | | 2 | | |
| Rotalia" translucens | | | 8 | | | | | | | | | | |
| iphotextularia rolshauseni | | | | | | | | | | | | | 8 |
| piroloculina sp. | | | | 2 | | | | | | | | | |
| pirophthalmidium acutimargo | | | | | | | 2 | | | | | | |
| retomphalus atlanticus | 43 | | 2 | | | | | | | | | | |
| vigerina hollicki | | | | 2 | | | | | | 2 | 4 | 8 | |
| irgulina advena | 1 | | | | 10 | 9 | 6 | 2 | | | 2 | | |
| . complanata | | | | | | | 4 | 2 | | | | | |

eption. No interpretation of chronology has een made of this core. It is suggested nat more than one displacement may have eposited this material.

TABLE 7. Occurrences of Foraminifera in selected samples from Core 229 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 229 DEPTH-4,810 M | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 4 | 9 | 11 | 16 | 17 | 21 | 23 | 24 | 27 | 29 | 31 | 33 | 36 | 41 | 46 | 48 | 50 | 54 | 59 | 61 | 62 | 67 | 73 | 76 | 79 | 86 | 90 | 102 |
| CM. FROM TOP OF CORE | 1.5-2 | 19.5-20 | 69.5-70 | 89.5-90 | 139.5-140 | 149.5-150 | 191-191.5 | 209.5-210 | 219.5-220 | 249.5-250 | 269.5-270 | 289.5-290 | 309.5-310 | 339.5-340 | 389.5-390 | 439.5-440 | 459.5-460 | 479.5-480 | 519.5-520 | 569.5-570 | 589.5-590 | 599.5-600 | 649.5-650 | 709.5-710 | 739.5-740 | 769.5-770 | 839.5-840 | 879.5-880 | 999.5-1000 |
| PLANKTONIC POPULATION | 1,550 | 100 | 550 | 2,400 | | 1,150 | 1,650 | | 3,000 | 5,400 | 1,650 | 11,400 | 4,450 | 2500 | 3,800 | 100 | 800 | 8,650 | 3,250 | 10,200 | 125 | 1,300 | 1,250 | 3,300 | 62 | 0 | 32 | 3,150 | 4,700 |
| Globigerina bulloides | 12 | 2 | 2 | 3 | | 6 | 5 | | 2 | 5 | 3 | 8 | 7 | 3 | 2 | 4 | 2 | 6 | 6 | 15 | 13 | 10 | 1 | 9 | 2 | | | 1 | 3 |
| G. digitata | | 1 | | .7 | | | .5 | | 1 | | 2 | | | | 2 | | .5 | | | | | .6 | | .5 | 2 | | | .5 | |
| G eggeri | 25 | 68 | 55 | 43 | A | 43 | 40 | C | 16 | 14 | 18 | 5 | 25 | 37 | 18 | 15 | 23 | 6 | 22 | 29 | 33 | 30 | 46 | 23 | 50 | | 69 | 45 | 64 |
| G. hexagona | | | | | | | 3 | | | 1 | | 6 | 1 | | | | 1 | 10 | | | | | | 7 | | | | | |
| G. inflata | 12 | 3 | 22 | 19 | A | 23 | 13 | | 2 | 8 | 6 | | 18 | 4 | 8 | 3 | 3 | 2 | .5 | 11 | 14 | 26 | 8 | 1 | 10 | | 6 | 1.5 | 14 |
| G pachyderma | 2 | 2 | 3 | 2 | | | 5 | | 3 | | | | | .8 | .8 | | 2 | | | .6 | | | | | | | | | 3 |
| G. quinqueloba | | | | | | | | | | | | | | | .4 | | | | .5 | | | | | | | | | | |
| Globigerinella aequilateralis | | | | 1 | | | | | | 1 | | 3 | 2 | | .4 | | 2 | .4 | .5 | .6 | | | | .5 | | | | | |
| Globigerinita glutinata | .5 | | | | | | .5 | | | .6 | | .6 | .7 | | | | | .8 | | 2 | .8 | .6 | | .5 | | | | | |
| Globigerinoides conglobata | .5 | | .4 | 2 | R | | | | | 2 | | 3 | .4 | 3 | 2 | 3 | 4 | 3 | 1 | .3 | | | .6 | 2 | | | | 1 | |
| G. rubra | 24 | 2 | 5 | 3 | R | 11 | 13 | C | 3 | 25 | 4 | 28 | 18 | 5 | 10 | 1 | 12 | 36 | 14 | 25 | 24 | 13 | 2 | 15 | 5 | | | 5 | 4 |
| G. sacculifera | 13 | 1 | 5 | 12 | R | 6 | 12 | C | 3 | 11 | 3 | 11 | 16 | 4 | 6 | 1 | 5 | 14 | 13 | 7 | 6 | 9 | 1 | 19 | 8 | | | 6 | .6 |
| Globorotalia hirsuta | | 14 | 2 | | | 1 | 1 | | | | | | .4 | 3 | .4 | | 1 | | | .3 | | .6 | 1 | | | | | .5 | 1 |
| G. menardii | 2 → | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G menardii – tumida group | | | | | | | | A | 70 | 28 | 62 | 29 | 4 | 37 | 34 | 59 | 36 | 9 | 30 | 2 | 3 | 2 | 19 | 15 | 8 | | 25 | 35 | |
| G punctulata | 1 | 5 | 4 | 13 | C | 6 | 2 | | .5 | 1 | 2 | 1 | 2 | 3 | 6 | 12 | 3 | .8 | 5 | 2 | .8 | 1 | 15 | 4 | | | | 5 | 6 |
| G. scitula | 1 | 1 | | | | | 1 | | | | | .6 | | | | | | .8 | | .6 | | | | | 2 | | | | |
| G truncatulinoides | 2 | 1 | 2 | .7 | | .7 | 3 | | | .6 | R | R | 1 | .8 | 2 | 1 | | .8 | 2 | 1 | 2 | .6 | 2 | 1 | | | | .5 | 3 |
| G tumida | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | .5 | | .7 | .7 | R | 1 | | | 1 | 1 | | 3 | 3 | .8 | .4 | | 1 | 2 | | 1 | | .6 | .6 | .5 | | | | | |
| Pulleniatina obliquiloculata | 3 | | | .7 | | | .5 | | R | R | 1 | 2 | 2 | | 5 | 1 | 4 | 5 | 5 | 3 | 5 | 5 | 3 | 1 | 13 | | | 1 | 1 |
| Sphaeroidinella dehiscens | .5 | | | | | | | | | | | .6 | | | | 1 | | | .5 | | | | .3 | | 2 | | | | |
| BENTHONIC POPULATION | 25 | 65 | 100 | 80 | | 30 | 40 | | 30 | 40 | 80 | 85 | 45 | 40 | 70 | 40 | 50 | 40 | 100 | 85 | 9 | 45 | 100 | 45 | 2 | 60 | 25 | 80 | 95 |
| Cassidulina subglobosa | | | | | | | 3 | | 4 | 2 | | 6 | | 3 | | | | | | | | 5 | | 4 | 11 | | | 3 | 1 |
| Chilostomella oolina | | | | | | | | | | | | | 2 | | | | | | | | | | | 2 | | | | | |
| Cibicides robertsonianus | 4 | | 2 | 4 | | | 5 | | | | 1 | 2 | 2 | | 2 | | | 3 | | | | 2 | 1 | | 6 | | 4 | 1 | 2 |
| Eponides tumidulus | | | | | | | | | | | | | | | | | | | | 2 | | | | 2 | | | | | |
| E. umbonatus and variants | 8 | | | 4 | | 13 | 13 | | 11 | 5 | 8 | 4 | 20 | 5 | 6 | 8 | 8 | 5 | 4 | 2 | 11 | 2 | 9 | 9 | 22 | | 13 | 6 | 2 |
| Gyroidina lamarckiana | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | 3 | |
| G. orbicularis | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | 1 |
| G. soldanii variant | 12 | | | | | | | | | | 1 | | 2 | 5 | | 3 | 2 | 3 | 1 | | | | 1 | | | | | 1 | 4 |
| Eggerella bradyi | | | 2 | | | | 3 | | | 2 | 1 | 2 | 4 | | | | | 5 | 1 | 2 | | | 2 | 4 | 11 | 2 | 4 | 1 | 2 |
| Nonion barleeanum | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | |
| N formosum | | 2 | 2 | 1 | | 3 | 3 | | 4 | 2 | 4 | 2 | 4 | | | 5 | 4 | 5 | 7 | 6 | | 2 | 6 | | | | 4 | 1 | 12 |
| N pompilioides | 4 | 5 | 8 | 4 | | 3 | 13 | | 11 | 7 | 5 | 5 | 13 | 3 | 5 | 3 | 4 | | 6 | 12 | 22 | 7 | 2 | | | | | 4 | 5 |
| Planulina wuellerstorfi | 8 | 3 | 14 | 11 | | 17 | 10 | | 18 | 7 | 10 | 9 | 4 | 5 | 6 | 5 | 14 | 10 | 2 | 2 | | 9 | 6 | 7 | 6 | | 13 | 10 | 1 |
| Epistominella exigua | 12 | 13 | 14 | 32 | | 20 | 23 | | 15 | 18 | 19 | 12 | 20 | 18 | 32 | 24 | 23 | 26 | 26 | 19 | 33 | 14 | 10 | 22 | | 2 | 27 | 12 | 23 |
| E. umbonifera | 32 | 70 | 49 | 25 | | 20 | 8 | | 26 | 35 | 19 | 31 | 7 | 49 | 18 | 27 | 35 | 31 | 39 | 33 | 33 | 43 | 58 | 35 | 22 | 95 | 23 | 36 | 25 |
| Pullenia bulloides | 8 | 2 | 4 | 5 | | 10 | 13 | | 4 | 15 | 18 | 16 | 11 | 5 | 6 | 5 | 10 | 8 | 11 | 8 | | 2 | 4 | 7 | 6 | | 4 | 19 | 17 |
| P. quinqueloba | 4 | | 2 | 10 | | 7 | | | 7 | 2 | 1 | 4 | 9 | 5 | 23 | 11 | 2 | 5 | 2 | 5 | | 7 | | 2 | | 2 | 9 | 1 | 2 |
| P. sp. | | | 2 | | | | | | | | 9 | 2 | 2 | | | | | | | | | 2 | | | | | | | 1 |
| Pyrgo murrhina | 4 | | | 4 | | 3 | 3 | | | 2 | 4 | | | | 2 | 5 | | | 1 | 4 | | | 1 | | 11 | | | | |
| P. oblonga | | | | | | | | | | | | | | | | | | | 1 | 4 | | | 1 | | | | | | |
| Quinqueloculina venusta | 4 | | | | | 3 | | | | | | 1 | | 3 | | | | | | | | 5 | | | | | | 1 | |
| Q. cf. weaveri | | | | | | | | | | | | 1 | | | | | | | | | | | | 2 | | | | | |
| Robulus | | | | | | | 3 | | | | | | | | | 3 | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 5 | | 2 | | | | | | | | | | | | | | | | 1 | | | | | | | | | |
| Textularia australis | | | | | | | | | | | | | | | | | | | 1 | | | | | 2 | | | | | |
| Uvigerina hollicki variant | | | | | | | | | | | | | | | | | | | | | | | | | 6 | | | | |
| Virgulina complanata | | 2 | | | | | 3 | | | | | | | | | | | | | | | | | | | | | | |

**Core 229.** The fauna in the top sample is not characteristic for the latitude, being more temperate in character than the normal low-latitude assemblage. At 69.5—70 cm. there is a fauna interpreted as typically mid-latitude in character. At 209.5—210 cm. the *Globorotalia menardii-tumida* group is abundant and the assemblage is interpreted as low-latitude. At 309.5—310 cm. there is a sharp decrease in frequency of *G. menardii-tumida* and an increase of *Globigerina inflata;* this is interpreted as representing more temperate conditions. At 339.5—340 cm. the low-latitude

fauna is indicated by the abundance of *Globorotalia menardii-tumida*, and the lower frequencies of the mid-latitude species. Another section showing mid-latitude affinities occurs between 569.5 and 640 cm., with a tropical suite of species coming in at 649.5 cm. and extending to 990 cm. The bottom sample at 999.5—1,000 cm. has a high frequency of *Globigerina inflata*, *G. pachyderma*, and no *Globorotalia menardii-tumida*, and is of a mid-latitude type.

Most of the samples in this core show evidence of abundant solution of calcium carbonate as shown by the high percentage of broken shells. Samples in which there is relatively little broken shell are at 289.5—290 cm. and at 569.5—570 cm. The relative abundance of *Pulleniatina obliquiloculata* in sample 76 at 739.5—740 cm. appears to be due to the selective solution of other species which probably originally were present in great abundance.

*Globigerina hexagona* occurs only deeper than 191 cm. *Globorotalia tumida* is present only in the top sample at 1.5—2 cm. *G. menardii* is present to a depth of 990 cm.

**Core 230.** This core appears to be composed entirely of red clay and contains evidence of abundant solution of calcium carbonate. Solution effects are especially striking in the upper 10 or 11 meters of the core in which there are only a few specimens of Foraminifera in a few samples. One lower section of the core, between 1409.5 and 1,470 cm. has relatively little solution effect in most samples. The sample at 1,299.5—1,300 cm. showed somewhat less solution than most of the other samples. No reliable interpretation of the Foraminifera in the upper two—thirds of the core can be made because there is little record at all, and no continuous record.

At 5.5—6 cm. two specimens, *Globigerina bulloides* and one specimen of *Globorotalia scitula* were identified, and in addition there are a few juvenile specimens of *Globigerina*

TABLE 8. Occurrences of Foraminifera in selecte samples from Core 230 in percent of total populatio Planktonic and benthonic populations computed separately.

| CORE 230 DEPTH-5,500 M. | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1A | 39 | 98 | 103 | 106 | 110 | 115 | 119 | 123 | 128 | 131 | 133 | 140 | 143 | 145 | 149 |
| CM. FROM TOP OF CORE | 5.5-6 | 379.5-380 | 969.5-970 | 1019.5-1020 | 1048-1048.5 | 1089.5-1090 | 1139.5-1140 | 1179.5-1180 | 1219.5-1220 | 1269.5-1270 | 1299.5-1300 | 1319.5-1320 | 1379.5-1380 | 1409.5-1410 | 1429.5-1430 | 1469.5-1470 |
| PLANKTONIC POPULATION | 3 | 25 | 60 | 75 | 330 | 1,400 | 450 | 300 | 3,200 | 1,400 | 4,700 | 5,400 | 400 | 7,300 | 22,500 | 3,400 |
| Globigerina bulloides | 67 | 44 | 5 | | 1 | 3 | 3 | 10 | 4 | 2 | 1 | 7 | 4 | 3 | 5 | 5 |
| G. digitata | | | | | .3 | | | | | | | | | | | |
| G. eggeri | | 7 | 53 | 34 | 44 | 39 | 22 | 22 | 57 | 57 | 26 | 32 | 22 | 27 | 21 | 23 |
| G. inflata | | | | | 3 | .6 | .4 | | 2 | 1 | .7 | 4 | .8 | 1 | | .7 |
| G. pachyderma | | | | | .6 | | .2 | | | | | .6 | | | | .2 |
| G. quinqueloba | | 11 | | | | | | | | | | | | | | |
| Globigerinella aequilateralis | | | | | | | | | | | | | | | .6 | |
| Globigerinita glutinata | | 26 | | 1 | | 1 | .2 | 2 | | .6 | .3 | | .5 | .4 | 1 | 1 |
| Globigerinoides conglobata | | | 2 | | .3 | 3 | .7 | 2 | | .6 | 3 | 2 | 1 | 3 | .6 | 1 |
| G rubra | | | 7 | 8 | 11 | 24 | 42 | 46 | 12 | 6 | 34 | 17 | 42 | 25 | 38 | 41 |
| G. sacculifera | | | 5 | 21 | 8 | 10 | 10 | 14 | 12 | 11 | 17 | 10 | 12 | 19 | 18 | 10 |
| Globorotalia hirsuta | | | 3 | | .3 | .6 | | | | | | | .2 | | | |
| G. menardii-tumida group | | | | 3 | 22 | 4 | 11 | 5 | 1 | 2 | 2 | 15 | 8 | 14 | 9 | 11 |
| G. punctulata | | | | | .6 | | 1 | .3 | 1 | 2 | 2 | | | | | |
| G. scitula | 33 | 11 | 2 | | | | | | | | | | .2 | | | |
| G. truncatulinoides | | | | | .6 | | .4 | | | | .3 | | .2 | | | |
| Orbulina universa | | | 3 | 4 | .3 | .6 | .9 | .3 | .5 | 2 | 2 | 4 | 1 | 4 | 2 | .7 |
| Pulleniatina obliquiloculata | | | | 8 | 3 | 1 | 2 | 1 | 6 | 9 | 1 | 2 | 2 | 2 | 2 | 1 |
| Sphaeroidinella dehiscens | | | 20 | 22 | 5 | 13 | 7 | 5 | 3 | 6 | 11 | 6 | 8 | 3 | 4 | 4 |
| BENTHONIC POPULATION | 0 | 0 | 10 | 2 | 40 | 25 | 15 | 9 | 100 | 40 | 40 | 50 | 9 | 70 | 50 | 14 |
| Cassidulina subglobosa | | | | | | | | | | 3 | | 9 | | 1 | .6 | |
| Cibicides robertsonianus | | | | | | 4 | 7 | | 1 | | | | | 1 | 4 | 7 |
| Eponides umbonatus and variants | | | | 50 | 2 | 7 | 20 | 22 | 17 | 27 | 3 | 22 | 11 | 25 | 13 | 14 |
| Gyroidina lamarckiana | | | | | | 4 | | | 1 | | 3 | 2 | | 1 | | |
| G orbicularis | | | | | | | | | | | | | | 1 | | |
| G. soldanii variant | | | | | | | | | | | | | 11 | | 2 | |
| Eggerella bradyi | | | | | | | 7 | 11 | | 6 | 11 | 4 | | 6 | | 7 |
| Nonion formosum | | | | | | 15 | 7 | | 5 | 8 | 8 | | | | 8 | |
| N pompilioides | | | 10 | | 7 | 11 | | 11 | 3 | 5 | 14 | 9 | | | 11 | 7 |
| Planulina wuellerstorfi | | | 10 | | 2 | | 13 | 22 | 6 | 5 | | 4 | 11 | 6 | | |
| Epistominella exigua | | | 20 | | | 7 | 7 | | 9 | 3 | 8 | 4 | | 3 | 4 | |
| E. umbonifera | | | 50 | 50 | 84 | 26 | 20 | 11 | 31 | 26 | 33 | 11 | 56 | 21 | 26 | 14 |
| Pullenia bulloides | | | | | | 18 | 13 | 22 | 15 | 11 | 6 | 7 | 11 | 9 | 13 | 14 |
| P. quinqueloba | | | 10 | | | 4 | 7 | | 7 | 5 | 11 | 20 | | 15 | 6 | 29 |
| P sp | | | | | 5 | 4 | | | 3 | | | 4 | | | 2 | 7 |
| Pyrgo murrhina | | | | | | | | | 3 | | 3 | 4 | | 1 | | |
| Quinqueloculina venusta | | | | | | | | | | | | | | 3 | 4 | |
| Q. cf. weaveri | | | | | | | | | | | | | | | 2 | |
| Siphotextularia rolshauseni | | | | | | | | | | 3 | | | | | | |

*inflata*. These few specimens definitely indicate an assemblage different from that livin in this tropical region at present, and on characteristic of the present mid-latitude regio of the North Atlantic. The surface sampl collected with the short coring tube at th same station contains a typical low-latitud fauna. It appears obvious that the long cor samples from 5.5—6 cm. does not represen the modern conditions at this place, but i from a previous cycle.

Only three isolated specimens of Foraminifera are recorded from 6 cm. to 370 cm. A 379.5—380 cm. a very small »residual» faun suggests mid-latitude conditions. The next lowe sample containing Foraminifera is at 969.5—97 cm. It is suggested that this may represen essentially low—latitude conditions, becaus of the high frequency of *Globigerina eggeri*, low frequency of *G. bulloides*, presence of *Globigerinoides sacculifera*, and reduction in frequency of *Globorotalia scitula*. The frequencies shown in this sample have a low reliability, however, because of the very small population. At 1,019.5—1,020 cm. the fauna appears to be a definitely low—latitude one. The general abundance of *Globorotalia menardii-tumida* group, of *Globigerina eggeri*, *Globigerinoides sacculifera*, and *Pulleniatina obliquiloculata* in the rest of the lower part of the core seems to show low-latitude conditions during the time when this material was deposited.

**Core 232.** This core is composed of red clay. A large percentage of the Foraminifera is broken. Two large populations of complete tests occur at 67.5—68 cm. and at 119.5—120 cm.

TABLE 9. Occurrences of Foraminifera in selected samples from Core 232 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 232 DEPTH-4,975 M. | | | | | | |
|---|---|---|---|---|---|---|
| SAMPLE | 1 | 3 | 9 | 12 | 14 | 18 |
| CM. FROM TOP OF CORE | 5-5.5 | 12-12.5 | 67.5-68 | 99.5-100 | 119.5-120 | 158.5-159 |
| PLANKTONIC POPULATION | | 2,550 | 18,200 | 550 | 11,600 | |
| Globigerina bulloides | | | | 20 | 3 | P |
| G. eggeri | P | 28 | 79 | 14 | 41 | A |
| G. hexagona | | .6 | | .5 | | |
| G. inflata | | 3 | 1 | 17 | 2 | P |
| G sp 2 | | | | 1 | | |
| Globigerinella aequilateralis | | | | 2 | | |
| Globigerinita glutinata | | | | 6 | | |
| Globigerinoides conglobata | | | .7 | | 1 | |
| G rubra | | 2 | | 19 | 6 | P |
| G. sacculifera | | 4 | 9 | 2 | 24 | C |
| Globorotalia hirsuta | | | .7 | 3 | | |
| G. menardii-tumida group | | 58 | | | 14 | A |
| G. punctulata | P | 3 | 1 | | | |
| G. scitula | | | | 5 | | |
| G. truncatulinoides | P | | | 6 | | P |
| G. tumida | | | | | | |
| Orbulina universa | | | .7 | 5 | 4 | |
| Pulleniatina obliquiloculata | | 3 | 6 | | 4 | P |
| Sphaeroidinella dehiscens | | | .7 | | 1 | P |
| BENTHONIC POPULATION | | 60 | 100 | 6 | 200 | |
| Cassidulina subglobosa | | | 1 | 17 | 2 | |
| Chilostomella oolina | | | | | .5 | |
| Cibicides robertsonianus | | 6 | 3 | | 2 | |
| Eponides tumidulus | | 2 | | | | |
| E. umbonatus and variants | | 14 | 6 | | 8 | P |
| Eggerella bradyi | | 3 | 2 | | | |
| Nonion formosum | P | 6 | 7 | | 7 | P |
| N. pompilioides | P | | 3 | | 4 | P |
| Planulina wuellerstorfi | P | 11 | 2 | 17 | 3 | P |
| Epistominella exigua | P | 29 | 24 | 17 | 23 | |
| E. umbonifera | P | 15 | 38 | 17 | 30 | P |
| Pullenia bulloides | | 6 | 7 | 17 | 16 | |
| P. quinqueloba | P | 6 | 2 | | 2 | |
| P sp | | | | | .5 | |
| Pyrgo murrhina | P | | 3 | | 1 | P |
| Quinqueloculina cf. weaveri | | | 1 | | | |
| Siphotextularia rolshauseni | | | 1 | | | |
| Virgulina advena | | 2 | 1 | | 1 | |
| V. complanata | P | | | | | |

The undisturbed surface sample from the short core contains the normal low-latitude assemblage. The upper sample from the long core contains a fauna indentified from fragments which appears to be mid-latitude in affinities, and is therefore a previous cycle of deposition. At 12—12.5 cm. there is a low-latitude assemblage dominated by *Globorotalia menardii-tumida* and *Globigerina eggeri*, and also containing significant populations of *Pulleniatina obliquiloculata* and *Globigerinoides sacculifera*. At 67.5—68 cm. the fauna suggests somewhat cooler than low-latitude conditions. At 99.5—100 cm. the fauna contains an abundance of *Globigerina bulloides*, *G. eggeri*, *G. inflata*, *Globigerinoides rubra*, *Globorotalia scitula*, and *G. punctulata*, a typical mid-latitude assemblage. At 119.5—120 cm. there is another low-latitude fauna which continues to the bottom of the core at 159 cm.

**Core 233.** This core is composed entirely of mud with no apparent sand layers. The upper fauna is characteristic of the low-latitude assemblage. At 19.5—20 cm. there is an assemblage more mid-latitude in character. At 29.5—30 cm. there is a typical mid-latitude fauna extending to approximately 159 cm. At 168 cm. the fauna is interpreted as being slightly warmer, and at 220.5 cm. there is what appears to be a mid-latitude fauna. Between 230 and 280 cm. the fauna is intermediate in aspect, and from 290 to 370 cm. it appears to be typical low-latitude. There is a shift to a mid-latitude assemblage at 419.5 cm. and at 500 cm. the low-latitude fauna is present. A fauna of essentially low-latitude characteristics continues to the bottom of the core.

There is some indication of mixing of the planktonic fauna in samples at 390 cm. and at 930 cm., shown by relatively high percentages of *Globigerina inflata* along with high percentages of *G. eggeri* and the *Globorotalia menardii-tumida* group. Questionable evidence for depth displacement is seen at 1,150 and 1,250 cm. with the

TABLE 10. Occurrences of Foraminifera in selected samples from Core 233 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 233 | DEPTH- 4,125 M | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 3 | 4 | 8 | 13 | 17 | 18 | 23 | 24 | 27 | 29 | 30 | 32 | 37 | 38 | 40 | 41 | 43 | 46 | 51 | 54 | 59 | 63 | 70 | 72 | 77 | 82 | 88 | 96 | 97 | 108 | 113 | 118 | 120 | 128 | 133 | 143 | 148 |
| CM FROM TOP OF CORE | 1.5-2 | 19.5-20 | 29.5-30 | 68.5-69 | 119.5-120 | 158.5-159 | 168-168.5 | 220.5-221 | 229.5-230 | 259.5-260 | 279.5-280 | 289.5-290 | 309.5-310 | 359.5-360 | 369.5-370 | 389.5-390 | 399.5-400 | 419.5-420 | 449.5-450 | 499.5-500 | 509.5-510 | 579.5-580 | 619.5-620 | 689.5-690 | 709.5-710 | 749.5-750 | 801-802 | 850-850.5 | 930-930.5 | 939.5-940 | 1049.5-1050 | 1099.5-1100 | 1149.5-1150 | 1169.5-1170 | 1248-1248.5 | 1299.5-1300 | 1399.5-1400 | 1449.5-1450 |
| PLANKTONIC POPULATION | 52,700 | 15,700 | 3,550 | 4,450 | 4,200 | 5,700 | 4,900 | 250 | 75 | 4,400 | 23,000 | 7,900 | 27,800 | 11,300 | 50,000 | 12,000 | 5,400 | 3,000 | 1,725 | 3,700 | 31,000 | 7,100 | 18,250 | 9,550 | 8,075 | 29,700 | 45,500 | 6,800 | 1,000 | 6,300 | 300 | 300 | 3,750 | 75,700 | 55,600 | 49,700 | 9,950 | 16,600 |
| Candeina nitida | | | | | | | | | | | | | | | .2 | | | | | | | | | | | | | | | | | | | | .2 | | | |
| Globigerina altispira | | | | | | | | | | | | | | | | | | | | | | | | | | | R | | | | | | | | R | R | | |
| G bulloides | 2 | 7 | 13 | 4 | 3 | 5 | 3 | 1 | 1 | 4 | 3 | .8 | 1 | 1 | 2 | 5 | 5 | 3 | | 2 | 9 | 1 | 3 | 1 | 2 | 8 | 2 | 5 | | 1 | 1 | .3 | 2 | 2 | 1 | .5 | .6 | .3 |
| G digitata | | 4 | .4 | .7 | | | | 8 | | | | | | | | .3 | | .5 | | | | | | .7 | .4 | .4 | | .5 | | | .7 | .3 | | .3 | | | | |
| G eggeri | 10 | 24 | 23 | 26 | 38 | 30 | 56 | 40 | 34 | 47 | 16 | 28 | 18 | 18 | 4 | 13 | 18 | 34 | 49 | 16 | 15 | 20 | 4 | 11 | 14 | 5 | 22 | 47 | 18 | 19 | 48 | 60 | 51 | 12 | 24 | 31 | 66 | 50 |
| G hexagona | | | 2 | .7 | .4 | .7 | | | | .4 | 3 | .8 | 3 | 4 | 5 | 6 | 6 | 1 | .5 | | | | 5 | | | | .6 | | 2 | 1 | | | .4 | 5 | | 1 | | .6 |
| G inflata | .2 | 2 | 3 | 7 | 10 | 5 | 3 | 15 | 1 | | 3 | 3 | .7 | | | 15 | 12 | 5 | 3 | 1 | 1 | | .7 | 1 | 4 | 1 | 2 | 3 | 8 | 1 | 6 | .3 | 1 | | .7 | .5 | 1 | 1 |
| G pachyderma | | 1 | 1 | | | .4 | .7 | | | | | | | | .2 | | | | | | | | .4 | | | | | | | | | | | | .2 | | | |
| G quinqueloba | | | | | | | | | | | | | | | | | .3 | | | | | | | | | .4 | | | | | | | | | | | | |
| G venezuelana | | | | | | | | | | | | | | | | | | | | | | | | | | | R | | | | | | | | | R | | |
| G sp 2 | | | | .7 | | | | | | | | | | | .2 | | | | | | | | | | | | | | | | | | | | .2 | | | |
| Globigerinella aequilateralis | 1 | 2 | 1 | 2 | 1 | 5 | | | | | .8 | .8 | .7 | 2 | 3 | 3 | 2 | .5 | | 2 | 3 | 3 | .7 | .7 | 2 | 3 | 2 | .5 | | 2 | .3 | .3 | 1 | 2 | 1 | | | .3 |
| Globigerinita glutinata | 5 | 9 | 14 | 11 | 2 | 4 | | | | .7 | 2 | | 1 | | 5 | 5 | 6 | 2 | | 1 | 5 | 4 | | | 6 | 8 | 2 | 1 | | .3 | .3 | | | 3 | 1 | 2 | | 1 |
| Globigerinoides conglobata | .2 | | 1 | 4 | .4 | .4 | 2 | | | 1 | .8 | | 1 | 4 | 1 | .8 | .6 | 2 | 4 | 3 | 1 | 1 | 3 | 2 | 1 | 1 | 1 | | 2 | 1 | .3 | | | 2 | .5 | .5 | 1 | 2 |
| G rubra | 26 | 31 | 9 | 6 | 10 | 17 | 5 | 11 | 8 | 5 | 28 | 7 | 23 | 10 | 30 | 23 | 27 | 16 | 15 | 27 | 30 | 20 | 21 | 14 | 29 | 26 | 28 | 7 | 6 | 4 | 11 | 3 | 2 | 24 | 26 | 18 | 4 | 12 |
| G sacculifera | 46 | 18 | 28 | 34 | 28 | 21 | 22 | 11 | 35 | 26 | 29 | 5 | 18 | 23 | 32 | 18 | 16 | 16 | 15 | 23 | 20 | 22 | 15 | 25 | 21 | 32 | 29 | 4 | 16 | 20 | 5 | 1 | 2 | 33 | 31 | 26 | 13 | 20 |
| Globorotalia hirsuta | 2 | 4 | 1 | | 4 | .4 | | | | | | | | | | .5 | .6 | .5 | | | | | .4 | | | | .6 | | | | .3 | | | .3 | | .5 | | |
| G menardii | 3 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → | |
| G menardii-tumida group | | | | | 2 | | | | 4 | 3 | 7 | 49 | 28 | 30 | 13 | 6 | 2 | | 3 | 13 | 13 | 23 | 32 | 29 | 12 | 6 | 5 | 17 | 45 | 34 | 20 | 27 | 37 | 10 | 4 | 7 | R | |
| G multicamerata | | | | | | | | | | | | | | | | | | | | | | | | | | | R | | | | | | | | R | | | |
| G punctulata | 1 | .8 | | 7 | 4 | 2 | .7 | 3 | 5 | 7 | 4 | 2 | 2 | 5 | 1 | | .6 | 9 | 4 | 3 | 1 | 1 | 4 | 3 | 2 | 2 | 1 | 3 | | 4 | 1 | 6 | 3 | 2 | 1 | 3 | 7 | 5 |
| G scitula | | | | | | 3 | | 4 | | | | | | .6 | 2 | | .3 | | | 1 | | | | | .4 | | | | | | | | | | | | | |
| G. truncatulinoides | .7 | 2 | 3 | 1 | 1 | 3 | 3 | 10 | 8 | 3 | 2 | 2 | 1 | .6 | .2 | .3 | 1 | 6 | 4 | 8 | .6 | 1 | 1 | 3 | .4 | 4 | 1 | 2 | 3 | 3 | 4 | 3 | .4 | .2 | 1 | 1 | 3 | 1 |
| G tumida | 2 | — | — | — | — | — | — | — | → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G sp. 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | .6 | | | | | | | | .2 | 1 | | |
| Orbulina universa | 1 | 1 | | 1 | | 3 | 1 | 2 | 1 | .7 | 2 | 2 | 1 | .6 | 3 | 3 | 1 | 2 | 1 | | .3 | .3 | 2 | 3 | .8 | 3 | 1 | 1 | | 2 | 1 | 1 | | 1 | 4 | 5 | 2 | 3 |
| Pulleniatina obliquiloculata | 1 | 2 | | | .4 | .7 | 4 | 5 | 3 | 2 | .3 | | 1 | .6 | .8 | .8 | .6 | 3 | .5 | 1 | .6 | 3 | 8 | 5 | 6 | 5 | 1 | 2 | | 7 | | | .4 | .8 | 3 | 1 | 1 | 3 |
| Sphaeroidinella dehiscens | | | | | | | | | | | | | | 1 | | .5 | | | | | | | .4 | | | | | | | | | | 1 | 2 | 5 | 1 | 1 | .3 |
| S rutschi | | | | | | | | | | | | | | | | | | | | | | | | | | | R | | | | | | | | | | | |
| BENTHONIC POPULATION | 80 | 40 | 25 | 40 | 70 | 60 | 50 | 40 | 20 | 60 | 60 | 50 | 70 | 80 | 40 | 55 | 20 | 25 | 70 | 50 | 50 | 90 | 40 | 45 | 35 | 60 | 110 | 100 | 50 | 40 | 75 | 40 | 50 | 40 | 170 | 165 | 90 | 120 |
| Anomalina sp | | | | | | | | | | | | | 1 | | | | | | | | | | | | | 2 | | | | | | | | | 3 | 2 | 1 | |
| Bolivina cf. minuta | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B pseudopunctata | | | | | | | | | | 2 | 2 | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | |
| B. sp. 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | 1 | 1 | | |
| Bulimina alazanensis | | | 4 | 3 | | | | | | | | | | | | | | | | | | | | | | | 8 | | | | | | | | 3 | 3 | | |
| Buliminella sp | | | | | | | | | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | | 1 | | |
| Cassidulina crassa | | | | 10 | 3 | | | | | | | | | | | | | | | | | | | | | 2 | 2 | | | | | | 2 | | 17 | 11 | | |
| C. subglobosa | 2 | | 9 | 8 | 1 | 2 | 4 | 2 | | 3 | 3 | 13 | 15 | 4 | 22 | 8 | 6 | | 3 | 2 | 4 | 1 | 8 | | 3 | | 15 | 3 | 10 | 8 | 1 | | 2 | 5 | 19 | 24 | 7 | 3 |
| C reflexa | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | 2 | 3 | | |
| C sp 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | 1 | | |
| Chilostomella oolina | | | | | 1 | 14 | | | | | | | | | | 12 | 21 | | | | 2 | | | | 3 | 2 | | | | | 3 | | | | | | | |
| Cibicides lobatulus | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | | | |
| C robertsonianus | 1 | 2 | 8 | 3 | 3 | 7 | | | | 2 | | | 8 | 5 | 3 | 4 | | 9 | | | 2 | 1 | 10 | | | 2 | .5 | 3 | | | | | | | 1 | 2 | 1 | 4 |
| C. sp. | | | | | | | | | | | | | | | | | | | | | | | 3 | | | | 4 | 3 | 2 | | | | | | | 3 | | |
| Ehrenbergina undulata | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 3 | | | | | 8 | 4 | | |
| Eponides tumidulus | | | | | | | | | | | 3 | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | |
| E. umbonatus and variants | 6 | 2 | 4 | 15 | 3 | 14 | 14 | 5 | 5 | 5 | 16 | 2 | 9 | 17 | 8 | 4 | 10 | 5 | 4 | 13 | 2 | 8 | 8 | 2 | 3 | 2 | 5 | 5 | 12 | 5 | 3 | 10 | 11 | 12 | 2 | 3 | 4 | 4 |
| Globobulimina cf. turgida | | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | | | | | | | 1 | | |
| Gyroidina lamarckiana | 1 | | | | | | | | | | | | 1 | 3 | 3 | | | | | | | | | | | | | | | 5 | | | | 2 | .6 | | | |
| G orbicularis | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | |
| G. soldanii variant | 1 | 5 | | | 1 | | | | | 2 | 3 | | | | 3 | 2 | 6 | 5 | 1 | | | 3 | | 2 | 3 | 2 | 1 | 3 | 2 | 5 | | | 4 | 2 | 2 | 4 | | .8 |
| Eggerella bradyi | | 2 | | 3 | 3 | | | 2 | | 3 | 2 | 6 | 4 | 3 | | 2 | | | 1 | 2 | 2 | 4 | 3 | 2 | | 3 | 3 | | 2 | 8 | | | 9 | 5 | 3 | .6 | 1 | 2 |
| Laticarinina pauperata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .6 | | | |
| Nodosaria sps | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | | | 2 | | | |
| Nonion barleeanum | | | | | 1 | | 4 | | | 3 | 3 | 2 | | 5 | 8 | 8 | 6 | | | 4 | | 2 | 5 | | 6 | 2 | 1 | 1 | | | | | | | 1 | | | |
| N. formosum | 1 | | 4 | | 3 | 2 | | 5 | | 2 | 3 | 2 | 1 | 1 | | 2 | 6 | | 4 | 2 | 4 | 2 | 16 | 16 | | | 2 | 6 | 8 | 8 | | 10 | | | | | 10 | 9 |
| N germanicum | 10 | 14 | | 3 | 1 | 3 | 2 | | | 9 | 2 | 2 | | 1 | 3 | 9 | | | | | | | | | | | 1 | | | | | | | | .6 | 3 | | 10 |
| N pompilioides | 1 | | 9 | | 3 | 7 | 4 | 7 | | | 3 | 4 | 1 | 3 | 3 | 6 | 6 | 5 | | | 4 | 2 | | | 3 | 2 | 2 | 6 | | 5 | 4 | | | | | 1 | 4 | 3 |
| Nonionella atlantica | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | |
| Planulina wuellerstorfi | 21 | 7 | 13 | 5 | 8 | 7 | 10 | 5 | | 9 | 16 | 19 | 13 | 17 | 13 | 2 | 6 | 9 | 10 | 4 | 12 | 9 | 13 | 11 | 29 | | 11 | 4 | 19 | 16 | 3 | 5 | 23 | 12 | 1 | 10 | 8 | 5 |
| Epistominella exigua | 6 | 23 | 17 | 23 | 22 | 25 | 14 | 14 | | 17 | 13 | 6 | 12 | 16 | 3 | 6 | 6 | 31 | 12 | 15 | 32 | 18 | 10 | 20 | 18 | 17 | 9 | 26 | 14 | 13 | 5 | 33 | 4 | 7 | 2 | 3 | 17 | 23 |
| E. umbonifera | 29 | 14 | 9 | | 19 | 10 | 18 | 43 | 90 | 9 | 16 | 6 | 3 | 7 | 22 | 11 | | 5 | 60 | 37 | 28 | 40 | 5 | 27 | 18 | 50 | 9 | 25 | 19 | 13 | 70 | 28 | 25 | 32 | 5 | 5 | 22 | 26 |
| Pullenia bulloides | 7 | 16 | 13 | 13 | 8 | 2 | 16 | 10 | | 12 | 8 | 27 | 22 | 9 | 8 | 8 | 10 | 17 | | 9 | 2 | 5 | 10 | 9 | | 8 | 3 | 11 | 10 | 3 | 7 | 5 | 13 | 7 | 7 | .6 | 14 | 7 |
| P quinqueloba | 7 | | 4 | 3 | 8 | 7 | | | | 2 | 3 | 2 | | | | 6 | | 9 | 1 | 4 | 2 | 1 | 3 | 4 | 3 | 3 | 1 | 3 | | | 1 | | 4 | 7 | .6 | .6 | 4 | 2 |
| P sp. | | 2 | | 3 | | | | 2 | | 2 | | | 3 | | 3 | 4 | 6 | | 1 | 2 | | | | | | | 1 | 1 | 2 | | | | | | | | 2 | |
| Pyrgo murrhina | 1 | 2 | | 5 | 1 | | 8 | 2 | | 9 | | 4 | 3 | 1 | | | 6 | | | | 4 | 2 | | 2 | | 2 | 2 | | | 3 | | | | | .6 | .6 | 1 | .8 |
| P oblonga | | | | | | 2 | | | | 2 | | | | | | | | | | | | 1 | | | | 2 | 2 | | | | | 3 | | | | | | |
| Quinqueloculina venusta | 4 | 2 | | 3 | 1 | | 2 | | | | | | | 1 | | | | | | 2 | | | | | | | | | | | | | | 2 | | | 1 | .8 |
| Q. cf. weaveri | 1 | 5 | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Robulus | | | | | | | | | | | | | 1 | | | | | | | | | | 3 | | | | | | | | | | | | | | | |
| Rupertia stabilis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 5 | 7 | | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 2 | | | | | 2 | | | 2 | | | | | | 2 | | | | | | | | | | | | | | | | 3 | | 2 | | | | |
| Textularia australis | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | 1 | | | 3 | | | | 2 | | | | .8 |
| Uvigerina hollicki | | | | | | | | | | | | 2 | | 4 | | | | | | | | | 3 | | | | 9 | | | 3 | 1 | | | | 15 | 7 | | |
| U. hollicki variant | | | | | | | | | 5 | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | |
| Virgulina advena | | | 4 | | 7 | | | 2 | | 3 | | | | 1 | | | 6 | | 1 | | | | | | | | 1 | | | | | | | | | | | |
| V bradyi | | | | | | | | | | | 2 | | | | | 2 | | | | | | | | 2 | 12 | | 1 | | | | | | | | | | | |
| V complanata | | | | | | | | | | 2 | | 2 | | 1 | | | | 5 | | 2 | | | | | | | .5 | 1 | | | | | | | | | | |

presence of *Cibicides lobatulus* and *Nonionella atlantica*, both of which are considered questionable indicators of water shoaler than that now existing at this location.

*Globorotalia tumida* extends to 230 cm. *G. menardii* extends to 1,400 cm. *Globigerina altispira*, *G. venezuelana*, *Globorotalia multicamerata*, *G.* sp. 2, *Sphaeroidinella rutschi* and

TABLE 11. Occurrences of Foraminifera in selected samples from Core 234 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 234 DEPTH-3,577 M.

| SAMPLE | 1 | 3 | 8 | 13 | 18 | 22 | 25 | 30 | 33 | 36 | 41 | 44 | 48 | 53 | 57 | 62 | 65 | 70 | 75 | 77 | 82 | 87 | 92 | 97 | 98 | 101 | 103 | 104 | 108 | 109 | 110 | 113 | 118 | 123 | 128 | 130 | 131 | 137 | 138 | 143 | 147 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 0.5-1 | 19.5-20 | 69.5-70 | 119.5-120 | 169.5-170 | 209.5-210 | 239-239.5 | 289.5-290 | 319.5-320 | 349.5-350 | 399.5-400 | 429.5-430 | 469.5-470 | 519.5-520 | 559.5-560 | 609.5-610 | 639.5-640 | 689.5-690 | 739.5-740 | 759.5-760 | 809.5-810 | 859.5-860 | 909.5-910 | 959.5-960 | 967.5-968 | 999.5-1000 | 1019.5-1020 | 1029.5-1030 | 1069.5-1070 | 1079.5-1080 | 1089.5-1090 | 1119.5-1120 | 1169.5-1170 | 1219.5-1220 | 1269.5-1270 | 1289.5-1290 | 1299.5-1300 | 1357-1357.5 | 1362-1362.5 | 1409.5-1410 | 1449.5-1450 |
| PLANKTONIC POPULATION | 57,100 | 6,000 | 4,450 | 7,900 | 3,000 | 4,500 | 11,900 | 19,100 | 17,700 | 7,250 | 2,850 | 3,650 | 39,000 | 4,700 | 13,200 | 15,800 | 6,900 | 1,750 | 8,000 | 20,000 | 14,300 | 11,000 | 17,000 | 10,200 | 26,700 | 13,500 | 15,400 | 22,200 | 21,000 | 5,570 | 32,800 | 14,700 | 11,800 | 20,700 | 16,200 | 15,200 | 19,000 | 17,500 | 14,000 | 26,500 | 18,500 |
| Candeina nitida |  | .6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  |  |  |  |  |  | .6 |  |  |  | 1 | .4 |  | .7 |  |  |  | .3 |
| Globigerina altispira |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | R |  |  | R |  |  | R | 5 | 2 | 3 | 6 |  | 6 | .4 | 4 | 8 |  |
| G. bulloides | 1 | 3 | 2 | 4 | 6 | 4 | 3 | 3 | 5 | 6 | 2 | 1 | 3 | 1 | .5 | 3 | 7 | 6 | 2 | 3 | 5 | 6 | 4 | 2 | 3 | 9 | 5 | 5 | 12 | 3 | 5 | 8 | 5 | 9 | 6 | 8 | 9 | 9 | 10 | 6 | 11 |
| G. digitata | .2 |  | .4 |  | .5 | 1 |  | .3 |  |  |  |  |  | .3 |  |  | 2 |  | .4 |  |  |  |  |  |  |  | .4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. eggeri | 8 | 17 | 22 | 34 | 18 | 38 | 23 | 19 | 7 | 16 | 26 | 30 | 9 | 22 | 6 | 16 | 23 | 34 | 31 | 34 | 30 | 30 | 29 | 21 | 20 | 17 | 13 |  | 7 | 40 | 17 | 11 | 13 | 14 | 15 | 11 | 9 | 28 | .1 | 8 | 15 |
| G. hexagona |  |  |  |  |  | .4 | 3 | 2 | 6 | .4 |  |  |  |  | .5 | .4 |  |  | .4 |  |  |  |  |  | .5 | 1 | 3 | .6 | 3 |  | 2 | 1 | .5 | 1 |  | 3 | .3 |  | 1 | 2 | 2 |
| G. inflata | .2 | 3 | 4 | 4 | 4 | 2 |  |  | 3 | 6 | .6 | 2 |  | .3 |  | .8 | 2 |  |  | .3 | .4 | 2 | 1 |  | .5 | 1 |  |  | 2 |  |  | .4 | .5 | 1 |  | .8 | .3 | .7 |  | 1 | .3 |
| G. pachyderma |  | .3 |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. quinqueloba |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .3 |
| G. venezuelana |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | R |  |  | R |  |  | R | 5 | R | 2 | 5 |  | 1 | .7 | 2 | 1 |  |
| G. sp. 2 | .4 |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  |  |  |  |  |
| Globigerinella aequilateralis | 3 | 2 | 1 | 2 |  | 1 | .5 | .6 | 2 | 2 | 1 | 2 | 5 | 1 |  | 2 | 1 |  |  | 2 | .4 | 3 | 2 | 1 | .5 | .7 | 2 | 1 | 1 | .6 | .4 | 1 | 2 | .3 | 2 | .4 | 2 | 3 | 1 | 3 | 3 |
| Globigerinita glutinata | 2 | 1 |  | .4 | 1 |  | 2 |  | 3 | 3 |  |  | 2 | 1 | 1 | .4 | 2 |  | .4 | 2 | 1 | .6 | 1 | 2 | 1 | 5 | 2 | 1 | 3 | .6 | .4 | 1 | .5 | 1 | .4 | 3 | 1 | 1 | 1 |  | 2 |
| Globigerinoides conglobata | .4 |  | 3 | .8 | 3 | .7 | .5 | 4 | 1 | 4 | 2 | 1 | 2 | .3 | 2 | 1 | .5 | .5 | .8 | .3 |  | .6 | 1 |  | 2 | 1 | 2 | 1 | .6 | 1 |  | 1 | 1 | 1 | .8 | 3 | 1 |  | 1 | 1 | 2 |
| G. rubra | 30 | 22 | 27 | 16 | 16 | 12 | 11 | 12 | 33 | 33 | 20 | 13 | 24 | 27 | 33 | 32 | 37 | 10 | 15 | 25 | 29 | 32 | 25 | 26 | 25 | 28 | 28 | 28 | 26 | 16 | 23 | 21 | 26 | 22 | 14 | 31 | 22 | 22 | 22 | 14 | 25 |
| G. sacculifera | 45 | 48 | 36 | 32 | 43 | 32 | 20 | 20 | 28 | 21 | 38 | 18 | 31 | 23 | 24 | 22 | 15 | 13 | 20 | 25 | 25 | 19 | 27 | 32 | 25 | 21 | 33 | 27 | 29 | 10 | 29 | 26 | 38 | 26 | 24 | 26 | 19 | 25 | 24 | 27 | 24 |
| Globorotalia hirsuta |  |  |  |  |  | .4 |  |  | .4 | .4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4 |  | 1 |  | .5 |  |  |
| G. menardii | .4 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → |
| G. menardii-tumida group |  | R |  |  |  | 4 | 24 | 34 | 4 | R | .6 | 25 | 16 | 14 | 15 | 10 | 8 | 32 | 23 |  |  |  |  |  | 11 | 6 |  | 6 | .6 | 22 | 9 | 3 | 4 | 7 | 11 | 2 | 12 |  | 7 | 19 | 2 |
| G. multicamerata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | .5 | 1 | 2 | R | 3 | R | 4 | 5 |  |
| G. punctulata | 2 | 1 | 3 | .8 | 2 | 3 | 2 | 3 | .7 | 4 | 7 | 4 | 1 | 3 | 1 | 2 |  | 2 | 4 | 3 | 2 | 2 | 3 | 8 | 4 | .2 | 2 | 3 | R | 2 | .8 | .4 | .5 | 2 | 2 | 1 | .3 | 2 | 1 | 1 | 2 |
| G. scitula |  |  |  |  |  |  |  | 3 |  |  | .6 |  | .3 | .3 | 1 |  | .5 |  | .4 | .3 |  | .6 | .8 | .6 |  | 1 | .4 | .3 |  |  | .4 | 2 | 2 | .3 | .8 | .8 |  |  |  |  |  |
| G. truncatulinoides | 1 | 1 | .7 | 4 | 3 | 1 |  | 1 | .4 | 2 | 2 | 1 | 1 | .7 | .5 | .4 | 1 | .5 | .8 | R | .4 |  |  | 2 | .5 | .2 | 2 | 2 | R | 6 | .8 |  | .5 | .3 |  |  |  | .7 |  |  |  |
| G. tumida | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. sp. 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  | .8 | 5 | 2 | 2 |  |  | 4 | R | 2 |  |  |
| Orbulina universa | 1 | .6 | 1 | .4 | .5 |  | .5 | .3 | 5 | .4 | 1 | 3 | 3 | 3 | 3 | 3 | 1 |  | .8 | 1 | 1 | 2 | 1 | 2 | .5 | 3 | 3 | 3 | 12 | 3 | 4 | 1 | 2 | 2 | 4 | 5 | 3 | 3 | 5 | 4 | 4 |
| Pulleniatina obliquiloculata | 1 |  |  | .4 | 4 |  | 11 |  |  | 2 | R | 1 | 1 | 2 | 10 | 5 |  |  | .8 | 4 | 4 | 2 | 3 | 4 | 5 | 6 | 3 | 2 | 2 | .6 | 4 | 1 | 1 | 2 | .4 | 3 | .3 | 1 | .5 |  | 5 |
| [Sphaeroidina bulloides] |  |  |  |  |  |  |  |  |  |  |  |  |  |  | R |  | .5 | .5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Sphaeroidinella dehiscens |  |  |  |  |  | .4 |  | .3 | .7 |  |  |  |  |  | .5 |  |  | .5 |  | .3 | .4 |  |  |  | 2 | 1 | .8 | .3 | 2 |  | 2 |  | 2 | 1 | .8 | 2 | 4 | 1 | 1 | 2 | 2 |
| S. rutschi |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | R |  |  | R |  |  | R | 4 |  | 1 | .8 |  | 1 |  |  | 2 | .5 |
| BENTHONIC POPULATION | 95 | 50 | 50 | 70 | 100 | 115 | 60 | 140 | 80 | 20 | 70 | 50 | 160 | 60 | 45 | 80 | 65 | 30 | 65 | 170 | 95 | 80 | 80 | 140 | 150 | 140 | 95 | 90 | 120 | 140 | 100 | 80 | 60 | 100 | 50 | 100 | 90 | 40 | 40 | 50 | 75 |
| Anomalina sp |  |  |  |  |  |  |  | 5 |  | 5 |  | 2 | 3 | 2 | 7 | 4 | 2 | 6 |  | 2 | 8 |  | 3 | 3 | 3 | 3 | 2 | 5 | 3 |  | 1 |  | 2 | 2 | 4 | 3 | 2 |  |  | 4 |  |
| Bolivina pseudopunctata |  |  |  | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulimina aculeata |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B. alazonensis | 1 |  | 2 |  |  |  | 2 | 2 | 3 |  |  |  |  |  |  | 1 | 2 |  | 2 | 4 | 4 | 13 | 5 |  | 3 | 3 | 2 | 2 |  | 1 |  |  |  | 4 |  |  |  |  | 3 |  | 1 |
| Cassidulina subglobosa | 4 | 4 | 6 | 3 | 5 | 10 | 15 | 9 | 7 | 10 |  | 12 | 20 | 16 | 7 | 6 | 3 | 3 | 3 | 6 | 6 | 8 | 3 | 3 |  |  | 2 | 5 |  | 7 | 4 | 8 | 7 | 6 | 4 | 4 | 7 | 4 | 14 | 12 | 5 |
| Chilostomella oolina |  |  |  |  | 1 |  |  |  | 22 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |
| Cibicides kullenbergi |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4 | 4 |  |  | 3 |  | 1 |
| C. robertsonianus | 3 | 2 |  | 1 |  | 3 | 11 | 6 | 8 |  | 3 | 2 | 3 | 2 | 7 | 4 | 2 | 3 | 5 | 1 | 4 | 3 | 3 | 3 | 6 | 1 | 2 |  | 3 | 2 | 2 |  | 3 | 2 |  | 3 | 5 | .7 | 5 | 4 | 1 |
| C. sp | 1 |  |  |  |  |  |  |  | 3 |  |  | 2 |  | 2 |  | 1 |  | 3 | 2 | 5 | 4 | 5 | 8 |  | 3 | 1 |  |  | 3 |  |  |  | 2 | 2 |  |  |  | 1 |  |  |  |
| Dentalina sps. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 3 |  | 4 |  |  |  |  | 1 |  |  |  |  |  |
| Eponides tumidulus |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |
| E. umbonatus and variants | 3 | 14 | 8 | 6 | 9 | 8 | 10 | 8 | 7 | 5 | 6 | 13 | 3 | 2 | 7 | 13 | 6 | 9 | 5 | 9 | 4 | 5 | 3 | 8 | 5 | 7 | 4 | 5 | 7 | 9 | 4 | 10 | 13 | 10 | 16 | 3 | 13 | 7 | 5 | 16 | 14 |
| Glomospira charoides |  |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Gyroidina lamarckiana |  |  |  |  |  |  |  | 1 | 3 |  |  |  |  |  |  | 3 |  | 3 |  |  | 2 | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 | 1 | 3 |  |  |
| G. orbicularis | 3 |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. soldanii variant | 1 |  |  |  |  | 1 | 3 | .7 |  |  | 1 |  | 3 |  | 4 |  |  | 3 | 5 | 2 |  | 3 |  | 7 | 5 | 6 | 2 |  | 7 | 1 | 2 | 5 | 5 | 2 |  | 3 | 2 | 4 | 8 |  | 7 |
| Höglundina elegans | 6 |  |  |  | 1 | 2 | 2 | 1 |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eggerella bradyi |  | 4 | 2 |  |  | 3 |  |  | 5 |  |  |  | 3 |  |  | 3 | 2 |  | 3 |  | 4 |  | 3 | 3 |  | 1 | 2 |  | 3 | 1 |  |  |  |  | 2 | 2 | 3 |  |  |  | 4 |
| Laticarinina pauperata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  | 2 | 3 |  | 4 |  |  |  | 4 | 2 |  |  |  |  | 1 |
| Nodosaria sps |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |  |  | 3 | 7 | 15 | 5 | 7 |  | 4 | 3 | 5 | 2 | 4 | 7 | 3 |  |  |  | 5 |
| Nonion barleeanum |  |  |  | 4 | 2 | 7 | 8 | 7 | 5 | 21 | 4 | 8 | 8 | 10 | 2 |  |  |  | 2 |  |  |  |  |  |  | 1 |  |  | 3 |  | 4 | 5 |  | 2 |  | 4 |  |  |  |  | 3 |
| N. formosum |  |  |  | 3 | 1 |  |  | 1 |  |  |  |  |  |  |  |  | 2 |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 | 8 |  |  | 1 |  | 8 |  |
| N. germanicum | 10 | 8 | 10 | 10 | 2 | 5 |  |  |  |  |  |  |  |  | 2 | 4 |  |  | 2 | 5 | 4 | 3 | 5 | 8 | 8 | 7 | 6 | 2 | 7 |  | 9 | 13 | 13 | 10 | 8 | 5 | 10 | 14 | 9 | 20 | 4 |
| N. pompilioides |  | 6 | 6 | 3 | 4 | 4 | 5 | 6 |  |  |  | 2 |  | 6 | 4 |  | 2 |  | 2 | 7 |  | 10 | 18 | 10 | 3 | 1 |  |  | 3 | 3 |  | 5 |  | 2 | 2 |  | 2 | 1 | 3 |  |  |
| Osangularia cultur | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 7 |  |  |  |  |  |  |  |  |  |  |  |  |
| Planulina wullerstorfi | 22 | 18 | 37 | 19 | 11 | 9 | 5 | 14 | 10 | 16 | 13 | 17 | 18 | 11 | 7 | 11 | 21 | 19 | 20 | 32 | 25 | 13 | 10 | 17 | 16 | 12 | 19 | 14 | 7 | 21 | 23 | 8 | 13 | 12 | 16 | 19 | 12 | 25 | 17 | 8 | 14 |
| Pleurostomella acuminata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  | 2 |  | 2 | 1 |  | 5 |  |  |
| Epistominella exigua | 19 | 25 | 10 | 12 | 22 | 22 | 12 | 12 |  | 21 | 9 | 6 | 15 | 23 | 7 | 14 | 3 | 19 | 2 | 4 | 8 | 5 | 5 | 4 | 8 | 13 | 19 | 18 | 13 | 14 | 2 | 5 | 13 | 10 |  | 12 | 1 | 30 |  |  | 5 |
| E. umbonifera | 5 | 2 |  | 12 | 19 | 6 | 7 | .7 | 3 | 5 | 50 | 15 | 3 | 19 | 4 | 1 | 2 |  | 2 | 6 | 2 |  |  |  | 3 | 1 | 13 | 9 | 3 |  | 2 |  |  | 2 |  |  |  |  |  |  |  |
| Pullenia bulloides | 6 | 14 |  | 8 | 6 | 3 | 2 | 9 | 5 |  | 1 | 2 | 3 | 3 | 2 | 5 | 3 | 13 | 12 | 4 | 11 | 8 |  | 11 | 8 | 4 | 2 | 5 | 3 | 7 | 4 | 10 | 8 | 8 | 8 | 9 | 7 | 1 | 5 | 8 | 4 |
| P. quinqueloba | 3 |  | 4 | 1 | 3 | 4 |  |  | 7 |  |  | 12 | 18 | 2 | 7 | 8 | 11 | 6 | 17 | 4 | 6 | 5 | 13 | 6 | 3 | 4 |  | 5 |  | 13 | 4 | 3 | 3 | 12 | 4 | 1 | 10 | 3 | 8 | 16 | 5 |
| P. sp. | 2 |  |  |  |  |  |  | 1 |  |  | 1 | 2 |  | 2 |  |  |  |  |  | 1 |  |  |  |  |  | 1 |  |  |  | 1 |  |  |  |  |  |  |  | 2 |  |  | 4 |
| Pyrgo murrhina | 3 |  | 2 | 6 | 1 | 2 | 10 | 5 |  |  | 3 | 2 | 3 |  |  | 1 |  | 3 | 3 | 4 | 2 | 3 | 3 | 2 |  | 3 | 2 |  | 3 | 1 | 4 | 3 | 5 |  | 6 | 7 | 1 | 1 |  |  | 9 |
| P. oblonga |  |  | 2 | 4 |  | 1 |  | .7 | 3 |  | 1 |  |  |  | 2 |  | 9 |  | 3 |  | 2 |  |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Quinqueloculina venusta | 2 | 2 | 2 |  |  |  |  | 1 |  |  |  | 2 |  |  |  |  | 2 |  | 2 | 1 |  |  |  |  |  |  | 2 |  |  |  | 2 |  |  |  |  |  |  |  | 3 |  |  |
| Q. cf. weaveri | 3 |  | 4 |  |  |  |  |  | 3 | 5 |  |  |  |  | 2 | 3 |  |  |  |  |  |  | 3 |  |  | 1 |  | 2 |  |  |  | 3 | 2 |  |  |  | 2 | .7 |  |  |  |
| Robulus |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  | 5 | 3 | 1 |  |  | 2 |  |  |  |  |  |  |  |  | 1 |  |  | 3 |  |  |
| Sigmoilina schlumbergeri |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |
| S. tenuis |  |  |  |  | 2 |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Siphotextularia rolshauseni |  |  |  |  | 1 | 1 |  | 1 | 5 |  | 1 |  |  |  |  |  | 2 | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |
| Textularia australis |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  | 4 | 1 |  |  |  |  |  |
| Uvigerina hollicki |  |  |  |  | 5 | 9 | 7 | 8 |  | 5 |  | 2 |  |  | 29 |  | 4 | 6 | 6 | 4 |  | 10 | 15 | 4 | 24 | 19 | 2 | 18 | 10 | 13 | 11 | 10 | 3 | 8 | 2 | 6 | 2 | 1 | 3 |  | 7 |
| U. hollicki variant |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 13 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  |  |  | 1 | 3 |  |  |  |  | 5 |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |  | 3 |
| V. bradyi |  |  |  |  |  | 1 | 2 |  |  |  | 1 |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| V. complanata |  | 2 |  | 1 |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  |

*Cassidulina reflexa* occur in a few samples below 800 cm.; these forms are of Oligo-Miocene or Miocene age.

**Core 234.** The top fauna probably is not the modern fauna, according to the data from the surface sample taken at the same station; *Globorotalia menardii* is at low frequency in the top core sample, and *Globigerina inflata*

TABLE 12. Occurrences of Foraminifera in selected samples from Core 235 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 235 | DEPTH-4,560 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 10 | 14 | 17 | 20 | 23 | 26 | 27 | 31 | 36 | 42 | 44 | 50 | 54 | 55 | 66 | 71 | 76 | 81 | 86 | 88 | 94 | 95 | 99 | 101 | 107 | 113 | 118 | 121 | 123 | 129 | 134 | 140 |
| CM. FROM TOP OF CORE | 0.5-1 | 39.5-40 | 89.5-90 | 129.5-130 | 159-159.5 | 189.5-190 | 220-221.5 | 249.5-250 | 259.5-260 | 299.5-300 | 349.5-350 | 409.5-410 | 430-430.5 | 489.5-490 | 529.5-530 | 539.5-540 | 649.5-650 | 699.5-700 | 750.5-751 | 799.5-800 | 849.5-850 | 869.5-870 | 929.5-930 | 939.5-940 | 979.5-980 | 999.5-1000 | 1059.5-1060 | 1119.5-1120 | 1169.5-1170 | 1199.5-1200 | 1219.5-1220 | 1279.5-1280 | 1329.5-1330 | 1389.5-1390 |
| PLANKTONIC POPULATION | 17,900 | 9,500 | 9,500 | 1,150 | 5,100 | 6,700 | 4,350 | 9,600 | 10,350 | 14,000 | 28,900 | 3,850 | 29,000 | 4,100 | 9,700 | 36,600 | 9,900 | 26,200 | 16,900 | 36,900 | 32,300 | 23,000 | 24,000 | 104,250 | 1,500 | 6,700 | 25,300 | 12,700 | 14,300 | 16,800 | 35,200 | 66,600 | 25,500 | 17,900 |
| Candeina nitida | | | | | | | | | | | | | | | | | | | | | | | .3 | | | | | | | | | | | |
| Globigerina bulloides | 7 | 3 | .7 | 3 | 2 | 2 | 5 | 2 | 2 | 11 | 1 | | 3 | 4 | | 1 | | .4 | .4 | | 1 | .6 | 2 | 6 | | .5 | 5 | .5 | 4 | 3 | 5 | 1 | 4 | 3 |
| G digitata | .4 | | .7 | .7 | | | | | | .5 | | | | .4 | | | | | | .7 | | | | | | | .4 | | | | | | | |
| G. eggeri | 8 | 17 | 23 | 44 | 17 | 11 | 5 | 24 | 19 | 15 | 46 | 20 | 8 | 54 | 41 | 14 | 60 | 37 | 49 | 35 | 22 | 58 | 25 | 7 | 58 | 40 | 37 | 31 | 41 | | 37 | 9 | 13 | 51 |
| G hexagona | | | | | 1 | .2 | 3 | | | | | | 3 | | | 4 | 2 | .7 | .8 | 5 | | | 2 | 6 | | 1 | .4 | | 1 | 2 | 1 | | | |
| G inflata | .4 | | 2 | 7 | .6 | 8 | 2 | 2 | .6 | 3 | 5 | 5 | | 6 | | | | 4 | 5 | 1 | 1 | 4 | 2 | .6 | 11 | 1 | 3 | 2 | 6 | 1 | 7 | .3 | | 4 |
| G pachyderma | | | | | | | | | | | | | | | | | | | | | .4 | 5 | | | | | | | | | | | 1 | |
| G quinqueloba | | .3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G sp. 2 | | | | | | | | | | | | | | | | | 1 | 1 | 1 | .7 | | | | | | | | | | | R | 3 | | 1 |
| Globigerinella aequilateralis | 1 | 4 | 3 | | .3 | 1 | .4 | | 1 | 5 | .7 | | 2 | 4 | | 1 | | .4 | .4 | | 2 | .6 | 2 | 9 | | .5 | 2 | | | .8 | .7 | .3 | | |
| Globigerinita glutinata | 2 | .7 | | .3 | .6 | 2 | 1 | | 1 | 1 | | | 5 | | | 3 | | 2 | .4 | 2 | 6 | | 1 | 24 | | | .8 | | | 3 | 3 | 1 | 2 | 1 |
| Globigerinoides conglobata | .4 | 1 | 4 | .3 | 1 | .7 | 3 | | .6 | 2 | 1 | .4 | 1 | | 1 | .7 | | .4 | 2 | 3 | 2 | .6 | 1 | | 2 | 1 | .4 | .5 | | 1 | .7 | | 4 | |
| G rubra | 24 | 31 | 5 | 12 | 19 | 16 | 24 | 9 | 16 | 17 | 1 | .8 | 23 | 6 | 3 | 19 | 4 | 12 | 3 | 12 | 22 | 2 | 28 | 32 | 1 | 3 | 11 | 2 | 7 | 19 | 6 | 34 | 24 | 5 |
| G sacculifera | 37 | 30 | 14 | 11 | 23 | 13 | 17 | 10 | 24 | 21 | 6 | 9 | 35 | .8 | 5 | 29 | 16 | 25 | 21 | 30 | 34 | 8 | 28 | 10 | 3 | 10 | 16 | 7 | 23 | 21 | 30 | 34 | 35 | 16 |
| Globorotalia hirsuta | | | | | | | | | | | | | .4 | 1 | .7 | .7 | 2 | .4 | | | .4 | | .5 | .3 | | | .4 | | | | | | 1 | 6 |
| G menardii | 6 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → | | | | |
| G menardii-tumida group | | 4 | 41 | 12 | 26 | 27 | 23 | 37 | 20 | 13 | 24 | 50 | 9 | 23 | 44 | 23 | | | | | | 19 | 5 | 2 | 22 | 34 | 20 | 34 | 1 | 8 | | | 1 | 1 |
| G. punctulata | 1 | 2 | 1 | 2 | 3 | 2 | 4 | 3 | 1 | 2 | 2 | 2 | .4 | | | | 5 | 3 | 2 | 1 | | | | .3 | | | | | .5 | .4 | | | | |
| G scitula | .7 | | | | .3 | | | | .3 | .5 | | | | | | | | | | | | | | | | | | | | | | .3 | | |
| G truncatulinoides | | 2 | .3 | 1 | .6 | 1 | .7 | .7 | 1 | .5 | .7 | 1 | 1 | 3 | .7 | .3 | 1 | .4 | 3 | 3 | .4 | .6 | 1 | .6 | 1 | | | | 2 | 1 | | .3 | | |
| G tumida | 6 | — | — | — | → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. sp 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | |
| G. sp 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | .4 | | | | | | | |
| Orbulina universa | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | .3 | .4 | 4 | .4 | | .7 | | 2 | 1 | 1 | .8 | 2 | 2 | 2 | | .5 | 2 | .5 | | 2 | .4 | 3 | 1 | 2 |
| Pulleniatina obliquiloculata | 4 | 3 | 6 | 4 | 4 | 13 | 1 | 11 | 12 | 7 | 10 | 12 | 4 | | 4 | 2 | 8 | 11 | 10 | 3 | 8 | .6 | 1 | .6 | | 5 | | 16 | 11 | 6 | 9 | 7 | 6 | 2 |
| [Sphaeroidina bulloides] | | | | | | | | | | | .3 | | | | | | | | | | | | | | | | .4 | | | | | | | |
| Sphaeroidinella dehiscens | .7 | .3 | | | .6 | 1 | | | | | | .4 | | | | .3 | | .4 | .4 | 1 | .4 | | .5 | | 1 | 2 | .4 | 7 | 3 | .4 | .4 | 4 | 3 | 6 |
| BENTHONIC POPULATION | 60 | 50 | 125 | 80 | 50 | 80 | 100 | 70 | 90 | 130 | 110 | 90 | 55 | 110 | 60 | 40 | 60 | 115 | 200 | 80 | 80 | 55 | 150 | 400 | 80 | 140 | 90 | 40 | 120 | 125 | 120 | 65 | 70 | 140 |
| Anomalina sp | | | | | | | 1 | 1 | | | | | 2 | | | | | | | | | | | 1 | | | | 3 | | | | | | |
| Bolivina pseudopunctata | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | 1 | | | | | | | |
| Cassidulina crassa | 11 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | |
| C subglobosa | | 7 | 2 | 2 | | 4 | 2 | 1 | 3 | 3 | 4 | 2 | | | 3 | 5 | 3 | 5 | 1 | 7 | 7 | | 1 | | | 3 | 5 | 6 | 5 | 2 | 2 | 6 | 3 | .7 |
| Chilostomella oolina | | | | | | | | | | | | 2 | | 20 | | | | | .5 | | | 2 | | 3 | | | | | | | | | | |
| Cibicides lobatulus | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | | | | | | | | |
| C robertsonianus | 3 | 4 | 2 | | | 6 | | | | 2 | | 2 | | | 2 | | 2 | 3 | 1 | 1 | | | .7 | | | | | 3 | 1 | | | 4 | | 5 |
| C sp. | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | |
| Ehrenbergina undulata | | | | | 2 | 1 | | | | .8 | | | | | | | | | | | | | | | | | 1 | | | | | | | |
| Eponides polius | | | | | | | | 1 | | | | | | | 2 | | | | | 1 | | | | | | | | | | .8 | | | | |
| E tumidulus | | 2 | | | | | | | | | | | 2 | | | | | | .5 | | | | | 1 | | | | | | | | | | |
| E. umbonatus and variants | 6 | 9 | 3 | 7 | 15 | 8 | 10 | 6 | 1 | 4 | 6 | 7 | 6 | 2 | 12 | 3 | 9 | 9 | 3 | 4 | 2 | 25 | 3 | 8 | 4 | 10 | 18 | 3 | 15 | 8 | 17 | 9 | 11 | 23 |
| Gyroidina lamarckiana | | | | | | | | | 1 | | | | 2 | | 2 | 5 | | 3 | .5 | | 1 | 2 | | 1 | | | 1 | | 1 | | 1 | | | 1 |
| G orbicularis | 2 | | | | 2 | | | | | | 3 | | | | | | | | | | | | | | | .7 | | 6 | 3 | | | | | |
| G soldanii variant | | 2 | | | | | 1 | | 2 | 2 | | | | | | | | | | | 1 | | | 1 | | | | | | .8 | | | 3 | |
| **Eggerella** bradyi | | | 2 | 1 | | 6 | 1 | 1 | 4 | 4 | 7 | 10 | | | 3 | 5 | 8 | 2 | .5 | 1 | 1 | 9 | .7 | 4 | 1 | | 5 | | 3 | | 1 | | 1 | 2 |
| Laticarinina pauperata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | | |
| Nonion barleeanum | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | 6 | | .8 | | | | |
| N formosum | | | 2 | 1 | 4 | 13 | 2 | 8 | 1 | 6 | 16 | 9 | 2 | | 2 | 3 | 23 | 7 | 7 | 7 | 7 | 7 | 4 | 3 | 9 | 3 | 5 | | 6 | 5 | 3 | 9 | 6 | 3 |
| N germanicum | 5 | 2 | | | | | | | | | | | | | | | | 3 | | 1 | | | .7 | 6 | | | | | | | 1 | 6 | 1 | |
| N. pompilioides | 2 | | 7 | 13 | | 3 | 4 | 1 | 2 | 11 | 10 | 1 | | | | | 3 | 3 | 3 | 2 | 8 | 11 | 3 | | 1 | 7 | 6 | 17 | 3 | 4 | 16 | | 3 | .7 |
| Planulina wuellerstorfi | 6 | 4 | 6 | 4 | 11 | 6 | 13 | 15 | 6 | 5 | 4 | 14 | 15 | 5 | 5 | 16 | 9 | 15 | 7 | 7 | 5 | 5 | 5 | 1 | 6 | 6 | 15 | | 8 | 7 | 5 | 9 | 7 | 8 |
| Plectina apicularis | 5 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Epistominella exigua | 10 | 17 | 18 | 37 | 19 | 17 | 14 | 35 | 22 | 24 | 9 | 24 | 23 | 20 | 25 | 13 | 19 | 27 | 24 | 20 | 26 | | 22 | 26 | 17 | 21 | 8 | 6 | 21 | 20 | 12 | 20 | 21 | 12 |
| E. umbonifera | 27 | 20 | 29 | 4 | 17 | 8 | 43 | 6 | 31 | 24 | 28 | 7 | 28 | 37 | 21 | 13 | 13 | 3 | 27 | 20 | 22 | | 32 | 3 | 34 | 23 | 2 | 17 | 11 | 34 | 3 | 14 | 31 | 25 |
| Pullenia bulloides | 11 | 15 | 21 | 7 | 13 | 11 | 4 | 9 | 14 | 10 | 11 | 12 | 11 | 4 | 13 | 21 | 6 | 9 | 15 | 25 | 9 | 2 | 17 | 10 | 13 | 10 | 25 | 19 | 9 | 6 | 16 | 5 | 6 | 11 |
| P quinqueloba | 3 | 7 | 6 | 16 | 6 | | 1 | 5 | 4 | 5 | 2 | 2 | 2 | 10 | 2 | 13 | | 3 | 5 | | 2 | 9 | 5 | 17 | 1 | 6 | 4 | | 3 | 6 | 5 | 1 | 1 | 2 |
| P sp | 3 | | | 5 | 4 | 1 | 1 | | | | | 1 | | | 2 | | | | | | 1 | 2 | | 1 | | | | | 2 | | 1 | 1 | 1 | |
| Pyrgo murrhina | 2 | 7 | .8 | 1 | | 6 | 1 | 5 | 1 | | 1 | | | | | | | 2 | 2 | 2 | 2 | 16 | .7 | 3 | 1 | 1 | 2 | | 4 | .8 | 3 | 3 | 3 | 3 |
| P. oblonga | | | | | | | | | | | | | | 2 | | | | | | | | 4 | .7 | 1 | | | | | | | | | | .7 |
| Quinqueloculina venusta | 2 | | | | 4 | 1 | | 1 | 2 | | | 2 | 6 | | 2 | 3 | 2 | 3 | | | 1 | | | | 1 | .7 | | | 1 | .8 | 1 | 3 | | |
| Q cf weaveri | 2 | 2 | | | | 1 | | | | | 1 | | 2 | | | | | 1 | .5 | | | 2 | | | | | | 3 | | .8 | 1 | 3 | | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .7 |
| Siphotextularia rolshauseni | | | .8 | | | | | 3 | 1 | .8 | | | | | | | | 1 | .5 | | | | .7 | 2 | | 2 | | | 2 | .8 | 2 | 1 | | 1 |
| Spiroloculina sp | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | | | | | | | | |
| Textularia australis | | | | | | | 2 | | 2 | | | | | | | | | 2 | | | | | | 1 | | 1 | | | | | 5 | | | |
| Uvigerina hollicki | | | | | | 1 | | | | | | | | | | | | | | | | | | 3 | | | | | | 8 | | | | |
| U hollicki variant | | | | | | 4 | | | | | | | | | | | 3 | | | | 4 | | 2 | | 11 | 4 | | | 2 | | | | | |
| Virgulina advena | | | | | | | | | | | | 2 | | | | | | | 1 | | | | | | | | | | 1 | | 3 | | | |
| V bradyi | | | | 1 | 4 | | 1 | | | | | | | | 2 | | | | .5 | | | | .7 | 2 | | | | | | | 3 | | | |
| V. complanata | | | | | | | | | 1 | | | | | | | | | | | | | 2 | | | | | | | | | | | | .7 |

is present but does not occur in the surface sample. At 19.5 to 160 cm. the fauna appears to be essentially mid-latitude, and at 170 to 229 cm. there is an intermediate assemblage. From 239 to 310 cm. the fauna is low-latitude, and from 320 to 390 cm. there is a mid-latitude fauna. The low-latitude assemblage is evidenced by high frequency of the *Globorotalia menardi*

*tumida* group at 430 to 750 cm. Below th layer from 750 to 968 cm. the fauna contain none of the *G. menardii-tumida* group but in other respects low-latitude.

At 968 cm. the fauna contains *Globigerin altispira*, *G. venezuelana*, and *Sphaeroidinel*

TABLE 13. Occurrences of Foraminifera in selected samples from Core 236 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 236 DEPTH-5,065 M

| SAMPLE | 1 | 3 | 5 | 8 | 11 | 12 | 14 | 19 | 22 | 25 | 27 | 28 | 29 | 36 | 39 | 40 | 46 | 48 | 50 | 53 | 56 | 57 | 63 | 66 | 72 | 75 | 78 | 82 | 85 | 90 | 93 | 94 | 95 | 97 | 99 | 103 | 110 | 115 | 121 | 126 | 131 | 140 | 144 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 0.5-1 | 19.5-20 | 39.5-40 | 69.5-70 | 99.5-100 | 109.5-110 | 129.5-130 | 179.5-180 | 209.5-210 | 240.5-241 | 259.5-260 | 269.5-270 | 279.5-280 | 349.5-350 | 379.5-380 | 391-391.5 | 449.5-450 | 468-468.5 | 479.5-480 | 509.5-510 | 539.5-540 | 549.5-550 | 609.5-610 | 639.5-640 | 699.5-700 | 729.5-730 | 761-761.5 | 799.5-800 | 829.5-830 | 879.5-880 | 909.5-910 | 919.5-920 | 929.5-930 | 949.5-950 | 969.5-970 | 1009.5-1010 | 1080.5-1081 | 1129.5-1130 | 1189.5-1190 | 1239.5-1240 | 1289.5-1290 | 1380.5-1381 | 1419.5-1420 |
| PLANKTONIC POPULATION | 5,000 | 20,000 | 11,900 | 730 | 420 | 430 | 2,150 | 700 | 2,600 | 5,400 | 210 | 1,600 | 30 | 2,300 | 350 | 1,600 | 1,200 | 7,500 | 6,100 | 430 | 6,000 | 2,200 | 2,100 | 6,800 | 3,800 | 310 | 650 | 1,050 | 27,000 | 900 | 15,350 | 2,400 | 3,450 | 4,700 | 8,000 | 350 | 80 | 180 | 3,100 | 650 | 1,450 | 1,500 | 35 |
| Candeina nitida | | | | | | | | | .3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | | | | | |
| Globigerina bulloides | 1 | 2 | 3 | | 1 | 5 | 6 | 2 | 10 | 4 | .5 | 2 | 7 | 7 | 1 | | 2 | 3 | | 12 | 7 | 10 | .8 | 17 | 4 | 4 | 7 | | 2 | 3 | 1 | 7 | 2 | 7 | 8 | 7 | 1 | | | 4 | 3 | | 2 |
| G. digitata | | | | | | | | | | | | | | | | | | | | .3 | | | | | | | | | | | | | | .3 | | | | | | | | | |
| G. eggeri | 19 | 15 | 17 | 54 | 36 | 53 | 54 | 51 | 44 | 52 | 75 | 39 | 28 | 38 | 49 | 40 | 30 | 18 | 16 | 38 | 33 | 25 | 52 | 27 | 34 | 27 | 15 | 13 | 6 | .4 | 17 | 13 | 14 | 2 | 19 | 21 | 35 | 32 | 14 | 53 | 28 | 76 | 23 |
| G. hexagona | | | | | | | | | | | | | | | | | | | | | | | | | 4 | | | | 2 | | | | | | | | | | | | | | |
| G. inflata | .3 | 6 | .5 | 9 | 6 | 19 | 14 | 13 | 8 | 8 | 6 | 5 | 4 | 1 | 5 | | | 1 | | 11 | 7 | 31 | 23 | 11 | 13 | 24 | 12 | 7 | | 12 | | 4 | 1 | 24 | 4 | 3 | 5 | 6 | 6 | 9 | 22 | .5 | |
| G. pachyderma | | .3 | 1 | 3 | 1 | .5 | .4 | 1 | 2 | .3 | | .5 | | 1 | | .5 | | | | | | | | 3 | | | | | | | | | | .3 | | | | | | | | | |
| G. quinqueloba | | | | | | | | | | | | | | | | | | 2 | 5 | | 1 | 1 | | 1 | | | | | | | | | .5 | | 1 | 1 | | | | | | | |
| Globigerinella aequilateralis | .6 | 2 | 3 | 1 | | 1 | | | .6 | .6 | .5 | .5 | 4 | 1 | .6 | | | | 1 | .3 | 3 | 2 | .8 | 3 | 3 | .6 | 1 | | 1 | 1 | 1 | .7 | | .7 | 2 | 1 | | | 1 | | 4 | | |
| Globigerinita glutinata | .3 | 1 | .5 | | | .5 | 2 | .6 | 6 | .3 | | 3 | 7 | 9 | | | | 2 | 1 | 1 | 8 | 8 | 2 | 6 | 2 | 3 | 1 | | 2 | | .7 | | | 5 | 2 | 4 | 1 | | | 3 | 6 | | |
| Globigerinoides conglobata | 1 | .3 | .3 | 2 | | .5 | .4 | | | 1 | | 1 | | .3 | | .5 | .7 | 3 | 3 | 2 | 2 | 1 | .8 | .3 | | | | 2 | 4 | 1 | 2 | .7 | 3 | 2 | 2 | .3 | | | | .3 | | | |
| G. rubra | 8 | 20 | 36 | 1 | 9 | 6 | 8 | 6 | 11 | 6 | 1 | 20 | 7 | 20 | 11 | 1 | .7 | 16 | 7 | 8 | 9 | 7 | 4 | 15 | 5 | 8 | 19 | 2 | .7 | 10 | 11 | 7 | 12 | 11 | 6 | 24 | 4 | .6 | 2 | 11 | 12 | | 6 |
| G. sacculifera | 27 | 35 | 23 | 20 | 20 | 12 | 7 | 17 | 8 | 16 | 2 | 17 | 17 | 9 | 7 | 3 | | 6 | 18 | 8 | 9 | 8 | 11 | 7 | 13 | 17 | 14 | 6 | 23 | 18 | 23 | 2 | 7 | 5 | 10 | 16 | 4 | 2 | 5 | 4 | 1 | | 5 |
| Globorotalia hirsuta | | | | | 1 | | | | .3 | | 2 | | | | | | | | | | | 1 | | 1 | | | | | | 5 | .3 | | | | | | | | | | | | .6 |
| G. menardii | 15 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → |
| G. menardii – tumida group | 1 | 14 | 5 | | 16 | 1 | | | R | | | | | | 2 | 42 | 58 | 35 | 41 | | 12 | | | 7 | 6 | 4 | 19 | 54 | 25 | .7 | 35 | 28 | 44 | 2 | 6 | 6 | 42 | 3 | 48 | .0 | 17 | 8 | 58 |
| G. punctulata | .3 | .3 | 1 | 5 | 2 | 2 | 3 | 4 | 2 | 1 | 3 | 3 | 4 | 1 | 6 | 2 | 2 | 3 | 1 | .5 | 3 | 1 | 2 | .6 | 3 | 4 | 4 | 2 | 4 | 6 | 2 | 2 | 1 | 2 | 4 | 2 | 5 | 8 | 2 | .3 | .6 | | 4 |
| G. scitula | .3 | | | | .5 | .5 | | | | .6 | | | 4 | 1 | | | | | | | .3 | | | | | | | | | | | | | | | | | | | | 1 | | |
| G. truncatulinoides | .6 | .6 | 1 | 3 | 2 | 2 | 5 | 6 | 7 | 4 | 3 | 2 | 4 | 5 | | .5 | | 2 | | 2 | 1 | 4 | 2 | | 3 | 1 | 2 | 2 | .5 | 1 | | 2 | 1 | .7 | 1 | 3 | 1 | 13 | 3 | 4 | 2 | 3 | |
| G. tumida | 8 | — | — | — | — | → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | .3 | 1 | | | 2 | 1 | 4 | | | .6 | | 3 | 4 | | 1 | .5 | | 2 | | .7 | .7 | 1 | .8 | 3 | .4 | 1 | 2 | | 2 | 4 | .7 | 1 | .5 | 2 | 2 | | | 1 | .5 | .6 | 3 | | |
| Pulleniatina obliquiloculata | 17 | 8 | 7 | 2 | 4 | | | | 1 | 6 | 7 | 6 | 10 | 5 | 11 | 9 | 5 | 6 | 9 | 11 | 3 | | | | 3 | 3 | 4 | 10 | 12 | 13 | 7 | 39 | 14 | 7 | 22 | 12 | 2 | 7 | 17 | | | | 2 |
| [Sphaeroidina bulloides] | | | | | | | | | | | | | | | | | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sphaeroidinella dehiscens | .3 | .3 | | | .5 | | | | | | | | | | | | .7 | .4 | 2 | | .3 | | | | | | | 2 | 5 | | | | | | | | | | 2 | | | | .6 |
| BENTHONIC POPULATION | 40 | 75 | 25 | 25 | 8 | 16 | 50 | 100 | 60 | 95 | 30 | 25 | 0 | 25 | 40 | 35 | 12 | 95 | 40 | 25 | 25 | 8 | 20 | 25 | 35 | 25 | 12 | 80 | 75 | 6 | 60 | 50 | 45 | 50 | 70 | 8 | 27 | 40 | 90 | 15 | 30 | 35 | 25 |
| Cassidulina subglobosa | 12 | 3 | | | | | | 1 | 2 | 4 | | | | | | 3 | 8 | 6 | 17 | | 4 | | | | | | | 2 | 9 | | 3 | 2 | 2 | | 1 | | 4 | 3 | 18 | | | | 4 |
| Chilostomella oolina | | | | | | 6 | 4 | | | | | 4 | | 13 | | | | 1 | | | | | | | | | | 1 | | | | | | | | | | | | | 3 | | 4 |
| Cibicides robertsonianus | 8 | 1 | 13 | | | | | | 2 | 2 | 4 | | | | | | | 4 | 5 | | 8 | | | | | | | 12 | 5 | | 3 | | 2 | 4 | | | | 5 | 1 | 7 | 3 | 5 | |
| Eponides pusillus | | | 4 | | | | 4 | | | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | | | | | | |
| E. tumidulus | | | | | | | | | | | | | | | 5 | | | | | | | | | | | | | | | | 3 | 2 | | | | | | | | | | | |
| E. umbonatus and variants | 10 | 8 | 4 | 17 | 12 | 12 | 2 | 7 | 5 | 17 | 11 | 12 | | | 10 | 12 | 25 | 15 | 3 | 13 | 15 | 13 | 5 | 4 | 3 | | | 14 | 10 | | 5 | 4 | | | 1 | 12 | 4 | 8 | 15 | | 7 | .3 | 15 |
| Gyroidina lamarckiana | | | | | | | | | | 1 | | | | | | | | 1 | | | | | | | | | | | 1 | | | 2 | | | | | | | 1 | | | | |
| G. orbicularis | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | |
| G. soldanii variant | 5 | 3 | | | | | | | | | | | | | 3 | | | | 2 | | | | | | | | | 1 | 3 | | | | 2 | | | | | | | | | | 7 |
| Eggerella bradyi | 5 | | 4 | | | 6 | | 1 | | 2 | | | | | | | 8 | | | | | | | | | | | 2 | 7 | | 7 | 4 | | | 7 | 12 | 7 | | .4 | | 7 | 8 | |
| Miliolids | | | | | | | | | | | | | | | | | | | | | | | | 13 | | | | | | | | | | | | | | | | | | | |
| Nonion formosum | 2 | | 18 | | | | 2 | 1 | | 6 | | 8 | | | 13 | 3 | | 4 | 2 | | | | | | | | | 4 | 7 | | 12 | 6 | 6 | | 7 | 12 | 15 | 5 | 4 | | | 19 | 11 |
| N. germanicum | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| N. pompilioides | 2 | 1 | 4 | 7 | | 12 | 2 | 4 | 12 | 3 | 7 | 21 | | | 5 | 6 | | 10 | | 8 | | 13 | 16 | 4 | 9 | 11 | 50 | 14 | 4 | | 7 | 8 | 13 | 16 | 20 | | 30 | 28 | 1 | 7 | 7 | 3 | 4 |
| Planulina wuellerstorfi | 8 | 4 | 9 | 14 | 25 | 12 | 10 | 6 | 8 | 4 | 7 | 17 | | | 31 | 12 | 8 | 3 | 10 | 8 | 7 | 25 | 16 | 13 | 6 | 7 | | 6 | 8 | 50 | 7 | 2 | 2 | 14 | | 12 | 19 | | 6 | 21 | 7 | 11 | 11 |
| Epistominella exigua | 8 | 20 | | | | | 4 | 4 | 17 | 20 | 31 | 4 | | 46 | 13 | 24 | 8 | 36 | 22 | 13 | 41 | 13 | 21 | 13 | 33 | 7 | 25 | 16 | 16 | | 17 | 17 | 28 | 6 | 23 | 25 | 7 | 26 | 22 | | 3 | 19 | |
| E. umbonifera | 30 | 25 | 31 | | | 31 | 53 | 64 | 27 | 5 | 20 | 17 | | | 10 | 9 | | 2 | 20 | | | | | 4 | | | | 16 | 7 | | 22 | 33 | 30 | | 4 | | 7 | 10 | 10 | | 50 | 5 | 15 |
| Pullenia bulloides | 8 | 16 | 9 | | | | | 1 | 5 | 18 | 4 | | | 29 | 8 | 6 | 25 | 6 | 7 | 8 | 4 | | | 8 | 6 | | 25 | 5 | 8 | 17 | 8 | 10 | 4 | 23 | 17 | | 4 | 10 | 11 | | 3 | 13 | 15 |
| P. quinqueloba | 2 | 5 | | 7 | 25 | | 12 | 4 | 10 | 5 | 4 | 8 | | | 3 | 6 | 8 | 2 | | 21 | 7 | 25 | 26 | 21 | 24 | 7 | | 1 | | | 3 | 6 | 6 | 14 | 4 | 12 | 4 | | 2 | | 7 | | |
| P. sp. | | 4 | | 4 | | | | 2 | | 1 | | 4 | | | | | 8 | 2 | 2 | | | | 5 | | 12 | 7 | | 2 | 3 | | 3 | 2 | | 12 | 3 | 12 | | | | 36 | | | |
| Pyrgo murrhina | | 1 | | 4 | 12 | | 2 | 1 | 5 | 2 | | 4 | | 4 | | 3 | | 4 | 2 | 4 | 7 | | 5 | 7 | 3 | | | | 5 | 17 | | | | 2 | 7 | | | | 1 | | 3 | 3 | 7 |
| P. oblonga | | | 4 | | | | | | 2 | 2 | | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | | | | 4 |
| Quinqueloculina venusta | | | | 7 | | | | | | | 4 | | | | | 3 | | | | 4 | | | | | | 4 | | | 3 | 17 | | | | 2 | | | | | | | | | 4 |
| Q. cf. weaveri | | | | | | | | | | 3 | 4 | | | | | | | | | | | | | | | | | 1 | | | | 2 | | | | | | | | | | | |
| Robulus | | 1 | | | | | | | | | 4 | | | | | | | 1 | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | | 3 | | | | | 2 | | | | | | | | | |
| Siphotextularia rolshauseni | | | | | | | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 3 | | | 5 | 1 | | | | |
| Spirophthalmidium acutimargo | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Textularia australis | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 2 | 2 | | | | | | | | | | |
| Virgulina advena | | | | | | | | | | 1 | | | | | | | | | 5 | | | | | | | | | | | | | | | | | | | | 1 | | | | |
| V. bradyi | | | | 40 | 25 | 12 | 2 | 1 | 3 | 1 | | | | 8 | | 9 | | 1 | 2 | 13 | 4 | | 5 | | 3 | 52 | | | 1 | | | | | | | | | | | 29 | | | |
| V. complanata | | | | | | 6 | | 2 | 2 | 1 | | | | | | | | | | 8 | 4 | 13 | | | | | | | | | | | | 2 | | | | | | | | | |

rutschi, all of which are considered to be not younger than approximately Upper Miocene n age. *Globorotalia* sp. 2 occurs at and below 1,030 cm., and *G. multicamerata* occurs at and below 1,120 cm. All of the modern species occur throughout the core and with the Tertiary fossil species, except *Globorotalia tumida* which s restricted to the upper 10 cm. *Globigerina hexagona* appears at 209.5—210 cm. and continues to the bottom of the core. The fossil ssemblage appears to be essentially a warm-water type.

Examination of this core showed the lower, Miocene section to be more compact and indurated than the upper section, especially below approximately 1,119 cm. There is an apparent lithologic discontinuity marked by a change in induration at 1,119 cm. which suggests a disconformity. Below this level the fossil species occur in relatively high percentages in all samples, and above this level the fossil forms occur rarely in only a few samples up to 967.5 cm. It appears likely that the contact at 1,119 cm. is in fact a disconformity and that the sporadic occurrence of the fossil specimens above this level is due to reworking.

There is neither faunal nor lithologic evidence for faunal displacement of sediment, and it is believed that the material represents more or less continuous deposition in the place where it was collected.

**Core 235.** It is suggested that the upper 640 cm. of this core contains an essentially uniform, low-latitude fauna. Small variations which occur are difficult or impossible to interpret. There are some layers where faunal mixing is apparent, as at 130 cm., at 190 cm., and at 980 cm. The section from 650 to 860 cm. appears to be mid-latitude in type with the absence of the *Globorotalia menardii-tumida* group but is low-latitude in other elements of the fauna. There is a low-latitude fauna from 870 to 920 cm., a somewhat intermediate fauna from 930 to 970 cm., a low-latitude assemblage from 980 to 1,160 cm., and an intermediate one from 1,170 cm. to the bottom of the core at 1,417.5 cm.

*Globigerina hexagona* occurs from 159 cm. to the bottom of the core. *Globorotalia tumida* is in the upper 159 cm. One specimen of *Globorotalia* sp. 2 occurs at 1,060 cm. *G. menardii* is present in the upper 1,200 cm. One specimen of *Cibicides lobatulus* at 750.5—751 cm. is very questionable evidence of faunal displacement; this core is composed of an apparently uniform mud and displacement is considered unlikely.

TABLE 14. Occurrences of Foraminifera in selected samples from Core 238 in percent of total population Planktonic and benthonic populations computed separately.

| CORE 238 | DEPTH-7,315 M. | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 42 | 45 | 48 | 51 | 54 | 58 | 69 | 71 | 74 | 83 | 86 | 90 | 103 | 108 | 113 | 120 | 121 | 129 | 140 | 149 |
| CM FROM TOP OF CORE | 389.5-390 | 420-420.5 | 449.5-450 | 479.5-480 | 509.5-510 | 549.5-550 | 659.5-660 | 674.5-675 | 684-684.5 | 766.6-767.2 | 788.5-789.5 | 819-819.5 | 949.5-950 | 999.5-1000 | 1029.5-1030 | 1083.6-1084.2 | 1089.5-1090 | 1162.4-1162.8 | 1264.5-1265 | 1349.5-1350 |
| PLANKTONIC POPULATION | 23 | 230 | 370 | 310 | 1,000 | 450 | 2,000 | 40,300 | 1,100 | 2,750 | 2,100 | 275 | 100 | 3,250 | 2,500 | 1,000 | 340 | 420 | 180 | 150 |
| Globigerina altispira | | | | | | | | | | | | | | | | | .6 | | 1 | |
| G. bulloides | 17 | 10 | 2 | 7 | 8 | 10 | 4 | 11 | .7 | 6 | 24 | 19 | 26 | 10 | 11 | 22 | 6 | 12 | 18 | 23 |
| G. eggeri | 9 | 32 | 32 | 37 | 30 | 34 | 37 | 32 | 39 | 51 | 22 | 34 | 36 | 36 | 39 | 28 | 29 | 41 | 32 | 37 |
| G. hexagona | | 1 | | | .8 | 1 | | | | 1 | 2 | .4 | | | .3 | .4 | | | | |
| G inflata | | 5 | 3 | 3 | 1 | 1 | 6 | 3 | 3 | 2 | 4 | 2 | 4 | 3 | 2 | | 3 | 3 | 1 | |
| G. pachyderma | | | | | .4 | .7 | | | .6 | 1 | | | 1 | | 1 | | | .7 | .6 | |
| G. quinqueloba | | | | | .4 | .2 | | | | | | | | | | | | | | |
| G. venezuelana | | | | | | | | | | | | | | | | | .6 | | | |
| Globigerinella aequilateralis | | 1 | | | | | | | | .6 | | | 1 | | .6 | | .3 | .2 | | |
| Globigerinita glutinata | 26 | 16 | 2 | 10 | 3 | 18 | .4 | 8 | .4 | .3 | 23 | 9 | 15 | 5 | 5 | 28 | 9 | 4 | 21 | 14 |
| Globigerinoides conglobata | | .4 | .8 | .6 | .4 | | .4 | | 1 | | | | | 1 | .3 | | | | | |
| G. rubra | 26 | 16 | 13 | 14 | 17 | 16 | 10 | 27 | 4 | 19 | 18 | 22 | 10 | 23 | 22 | 15 | 15 | 20 | 18 | 16 |
| G. sacculifera | 13 | 3 | 11 | 9 | 13 | 4 | 11 | 9 | 17 | 9 | 3 | 5 | 3 | 10 | 8 | 1 | 6 | 10 | 1 | 3 |
| Globorotalia hirsuta | | | | | | .5 | .4 | .6 | .4 | .3 | | | | | 1 | .4 | .6 | .5 | | |
| G. menardii-tumida group | | 5 | 8 | 7 | 7 | 3 | 14 | 2 | 4 | 3 | .8 | 1 | 1 | 2 | 3 | | 8 | 1 | 1 | 2 |
| G. multicamerata | | | | | | | R | | | | | | | | | | | | | |
| G. punctulata | | 1 | 4 | 3 | 5 | 3 | 4 | 3 | 6 | 1 | .4 | 4 | 1 | 3 | 3 | 2 | 6 | 3 | 1 | 1 |
| G. scitula | | 1 | | .3 | .4 | 1 | | | | | 2 | | 2 | | .6 | 2 | 1 | 1 | 1 | |
| G. truncatulinoides | 9 | 4 | 12 | 3 | 7 | 2 | 5 | 1 | 7 | 4 | 2 | | | 2 | 2 | 1 | 5 | 1 | 1 | .7 |
| G. sp. 2 | | 2 | 2 | .3 | .4 | 2 | | 1 | .7 | | | .7 | | 1 | 1 | | 2 | 1 | 3 | 1 |
| Orbulina universa | | 1 | 1 | | | | | | .7 | | | | | .5 | .3 | | | .2 | | |
| Pulleniatina obliquiloculata | | 1 | 8 | 4 | 6 | 2 | 7 | 2 | 18 | 2 | | 1 | | 1 | 1 | | 9 | 1 | | 1 |
| Sphaeroidinella dehiscens | | | .5 | | .4 | .2 | 2 | .3 | 1 | | | | | | | | .3 | | | |
| BENTHONIC POPULATION | 0 | 4 | 4 | 5 | 11 | 7 | 12 | 500 | 4 | 36 | 7 | 2 | 0 | 7 | 16 | 11 | 5 | 6 | 3 | 0 |
| Bolivina cf. minuta | | | | | | 14 | | | | | | | | | | | | | | |
| B. pseudopunctata | | | | 20 | | | | | | 3 | | | | | | | | | | |
| Bulimina alazanensis | | | | | 9 | | | 12 | | | | 50 | | | | | | | | |
| Cassidulina subglobosa | | | 50 | 20 | | 29 | 42 | 25 | 50 | 14 | 14 | | | | 38 | 9 | 40 | | 33 | |
| C. reflexa | | | | | | | | | | | | | | | 6 | 9 | | | | |
| C sp 2 | | | | | 9 | | 8 | | | | | | | | 6 | | | | | |
| Cibicides robertsonianus | | | | | 9 | 14 | | | 25 | 3 | | | | | 6 | | | | | |
| C. sp. | | | | | | | | | | 3 | 14 | | | | | 18 | | | | |
| Ehrenbergina trigona | | | 25 | | | | | | | 5 | | | | | | | | | | |
| Eponides umbonatus and variants | | 25 | | | | | 33 | | | 5 | | | | | 19 | 18 | | 18 | 33 | |
| Gyroidina orbicularis | | | | 40 | 9 | | 8 | | | 3 | | | | | 6 | | | | | |
| G. soldanii variant | | | | | | | | | 25 | | | | | 14 | | | | | | |
| Eggerella bradyi | | 25 | | | | | | | | | | | | | 6 | | | | | |
| Laticarinina pauperata | | | | | | 14 | | | | | | | | | | | | | | |
| Nodosaria sps. | | | | | | | | | | | | | | | | | | 9 | | |
| Nonion barleeanum | | | | | 9 | | | | | | | | | 28 | | | | | | |
| N. germanicum | | | | | | | | | | 3 | 14 | 50 | | | 6 | 9 | | | | |
| N. pompilioides | | | 25 | | 9 | | | | | 5 | | | | | | | | | | |
| Osangularia cultur | | | | 20 | | | | 12 | | | | | | | | | | | | |
| Planulina wuellerstorfi | | | | | 28 | | | | | 5 | | | | 28 | | | 20 | | | |
| Epistominella exigua | | | | | | | | | | 3 | 14 | | | | | 18 | | | | |
| E. umbonifera | | | | | | | | 12 | | 3 | | | | | | | | 18 | | |
| Pullenia bulloides | | 25 | | | | | | 25 | | 14 | 14 | | | | | 9 | | | | |
| P. quinqueloba | | | | | 9 | | | | | 3 | 14 | | | | | | | | | |
| P. sp. | | | | | | | | | | 6 | | | | | | | | | | |
| Pyrgo murrhina | | | | | | | | | | | | | | 14 | | | | | | |
| P. oblonga | | | | | | | | | | 3 | | | | | | | | | | |
| P. sps. | | | | | | | | | | | | | | | | | 20 | | | |
| Quinqueloculina cf. weaveri | | | | | 9 | | | | | | | | | 14 | | | | | | |
| Sigmoilina schlumbergeri | | | | | | | 8 | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 25 | | | | | | | | | | | | | | 9 | | | 33 | |
| Uvigerina hollicki | | | | | | 29 | | 12 | | 3 | | | | | 6 | | | | | |
| Virgulina bradyi | | | | | | | | | | 14 | 14 | | | | | | 20 | | | |
| V. complanata | | | | | | | | | | 3 | | | | | | | | | | |

**Core 236.** The top sample contains the same low-latitude fauna as the surface sample from the same station and this fauna appears to continue to 30 cm. An intermediate fauna between 40 and 60 cm. is suggested by decrease in the *Globorotalia menardii-tumida* group. At 70 cm. *G. menardii-tumida* is absent and *Globigerina inflata* is at higher frequency. There appears to be a total of at least five shifts to essentially mid-latitude faunas in the upper seven meters of this core, separated from each other by low-latitude assemblages. Below seven meters there are at least three layers which are interpreted as mixed faunas. There is a relatively high frequency of *Globigerinoides sacculifera* in most of the faunas in this core interpreted as mid-latitude.

*Globorotalia tumida* extends to 120 cm. *Globigerina hexagona* occurs at 700 cm. and at 830 cm. This core appears to be composed of

TABLE 15. Occurrences of Foraminifera in selected samples from Core 242 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 242 | DEPTH-3,620 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 2 | 5 | 10 | 15 | 19 | 21 | 24 | 25 | 26 | 31 | 33 | 36 | 37 | 40 | 42 | 45 | 47 | 49 | 54 | 57 | 62 | 68 | 73 | 77 | 80 | 85 | 90 | 94 | 95 | 99 |
| CM. FROM TOP OF CORE | 0-1 | 9.5-10 | 39.5-40 | 89.5-90 | 139.5-140 | 179.5-180 | 199.5-200 | 229.5-230 | 239.5-240 | 249.5-250 | 299.5-300 | 319.5-320 | 349.5-350 | 359.5-360 | 389.5-390 | 409.5-410 | 439.5-440 | 459.5-460 | 479.5-480 | 529.5-530 | 559.5-560 | 609.5-610 | 669.5-670 | 719.5-720 | 759.5-760 | 789.5-790 | 839.5-840 | 889.5-890 | 929.5-930 | 939.5-940 | 979.5-980 |
| PLANKTONIC POPULATION | 116,500 | 41,600 | 18,700 | 19,000 | 20,700 | 20,400 | 36,500 | 8,900 | 29,000 | 13,600 | 36,600 | 16,400 | 40,600 | 70,500 | 66,300 | 47,200 | 68,000 | 62,000 | 80,000 | 51,000 | 44,500 | 39,500 | 67,100 | 74,000 | 44,500 | 62,400 | 77,000 | 133,500 | 57,300 | 26,700 | 17,400 |
| Globigerina bulloides | 10 | 4 | 5 | 13 | 5 | 5 | 8 | 8 | 14 | 6 | 2 | 7 | 6 | 5 | 5 | 7 | 6 | 7 | 7 | 12 | 7 | 15 | 8 | 10 | 16 | 8 | 5 | 5 | | 5 | 5 |
| G eggeri | 10 | 8 | 15 | 20 | 18 | 27 | 44 | 52 | 34 | 38 | 28 | 15 | 17 | 17 | 14 | 12 | 29 | 21 | 23 | 28 | 14 | 15 | 40 | 16 | 13 | 30 | 15 | 14 | 29 | 51 | 35 |
| G. inflata | 1 | 2 | 4 | 8 | 1 | .3 | 1 | 4 | 2 | | .7 | .8 | 3 | 4 | 2 | 3 | 7 | 5 | 2 | 6 | .4 | 5 | 5 | .5 | 5 | 1 | .7 | .4 | 2 | 3 | 11 |
| G pachyderma | .2 | | | | .3 | | 3 | .4 | .3 | | | | .2 | .3 | .8 | | | 1 | 1 | .4 | .4 | | 2 | .3 | .4 | | .3 | | | .6 | |
| G. quinqueloba | | | | | .6 | .3 | | | | | | | | 1 | .8 | .4 | | .6 | .5 | | | .5 | | | 1 | | | | | .3 | .7 |
| Globigerinella aequilateralis | 4 | 2 | 5 | 2 | 4 | 2 | | | | 1 | 2 | 3 | .2 | 1 | .5 | 1 | .3 | .3 | 2 | 2 | 7 | 4 | 2 | 2 | R | 3 | .5 | 2 | 2 | 1 | 1 |
| Globigerinita glutinata | 5 | 2 | 3 | .7 | 2 | 2 | 3 | .7 | 3 | 2 | 8 | 11 | 14 | 16 | 14 | 13 | 5 | 7 | 7 | 9 | 9 | 11 | 6 | 12 | 23 | 15 | 11 | 9 | 4 | .6 | 7 |
| Globigerinoides conglobata | | .3 | 1 | 1 | | .6 | 1 | | .3 | .5 | .3 | | | .6 | R | .4 | .3 | R | .2 | R | 1 | 1 | R | .8 | 1 | | .5 | 1 | 2 | 2 | .4 |
| G. rubra | 38 | 27 | 28 | 15 | 34 | 19 | 15 | 12 | 20 | 17 | 15 | 29 | 30 | 27 | 29 | 24 | 18 | 27 | 24 | 12 | 27 | 13 | 13 | 30 | 19 | 9 | 19 | 29 | 17 | 5 | 20 |
| G. sacculifera | 18 | 33 | 15 | 14 | 19 | 15 | 4 | 11 | 10 | 8 | 15 | 22 | 18 | 30 | 21 | 21 | 10 | 15 | 15 | 13 | 17 | 13 | 9 | 11 | 9 | 7 | 13 | 14 | 27 | 18 | 10 |
| Globorotalia hirsuta | | | | | .3 | | .3 | | | | | | .2 | .3 | .8 | 2 | | .6 | | .8 | 1 | | .3 | .3 | | | | | .2 | | |
| G. menardii [G. tumida → no. 4] | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. menardii-tumida group | 4 | 13 | 12 | 9 | 8 | 16 | 18 | 3 | 12 | 24 | 21 | 4 | | .3 | R | | .3 | 6 | 15 | 9 | 10 | 17 | 14 | 13 | 8 | 19 | 15 | 13 | 1 | .3 | R |
| G. punctulata | .2 | | .3 | .7 | 1 | .3 | | .4 | .3 | 3 | 3 | 4 | 5 | 3 | 1 | 11 | 1 | .6 | | | 1 | | 1 | .3 | | | | | 1 | | R |
| G. scitula | .4 | .6 | | | | | | .4 | | | | | .2 | | | | | | | | | | | | | | | | .2 | | .4 |
| G. truncatulinoides | 2 | .6 | 2 | 10 | 4 | 8 | 2 | 8 | 5 | 1 | 1 | 3 | 4 | 4 | 7 | .4 | 13 | 7 | 3 | 7 | 1 | 1 | 1 | 1 | 3 | 1 | .7 | .3 | 2 | 5 | 8 |
| Orbulina universa | 3 | 1 | 2 | .3 | 2 | .3 | 1 | .7 | .3 | .5 | 1 | .4 | | .3 | .3 | .4 | .3 | .6 | .7 | .4 | 2 | 1 | .7 | .8 | R | .6 | .7 | .6 | 2 | 2 | .4 |
| Pulleniatina obliquiloculata | 2 | 3 | 6 | 6 | 2 | 4 | .3 | | | | .3 | 2 | 1 | 2 | 3 | 6 | 9 | 2 | .2 | R | 4 | 7 | | .5 | R | 9 | 17 | 13 | 11 | 6 | 2 |
| Sphaeroidinella dehiscens | | .3 | | | | | | | | | | | | | | R | .6 | R | | .4 | .5 | | | .3 | | | 1 | .1 | 1 | 2 | R |
| BENTHONIC POPULATION | 100 | 75 | 80 | 150 | 60 | 70 | 160 | 100 | 150 | 100 | 75 | 50 | 75 | 80 | 90 | 80 | 140 | 102 | 90 | 120 | 60 | 50 | 160 | 50 | 100 | 200 | 170 | 90 | 60 | 75 | 120 |
| Anomalina sp | 1 | | | | 4 | | | | | | | | 1 | 1 | 1 | | .7 | | 1 | | | 2 | | 2 | | 5 | 1 | 2 | | | |
| Bolivina globulosa | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | | | | |
| B. pseudopunctata | 1 | | | | | 1 | .6 | 1 | | | | | 4 | 1 | | | | | | | | | | | 1 | | | | | | |
| Bulimina alazanensis | | 3 | | | | | .6 | | | | | 4 | 3 | 4 | 1 | 3 | | | | | | | | 2 | | .5 | | 2 | 2 | | |
| B. translucens | | | | .7 | | | | 1 | | | | | | 1 | | | | | 1 | | | | 1 | | | | | | | 1 | 2 |
| Cassidulina carinata | | | | | | | | | | | | | | | | | | | | | | | | .5 | | | | | | | |
| C. crassa | | | | | | | 2 | | | | | | | | | | | 1 | | | | | .6 | | 1 | | | | | | .8 |
| C. subglobosa | 6 | 5 | 20 | 10 | 26 | 16 | 18 | 10 | 11 | 16 | 33 | 38 | 16 | 26 | 47 | 20 | 15 | 24 | 14 | 8 | 21 | 15 | 5 | 12 | 15 | 29 | 24 | 23 | 10 | 12 | 9 |
| Chilostomella oolina | 3 | | | | | 12 | | 4 | 1 | | 5 | | | | | | .7 | 1 | 1 | | | | | | | | | | | | |
| Cibicides robertsonianus | 2 | 4 | | .7 | | | 2 | | | 1 | 1 | 2 | 4 | 1 | 3 | 4 | .7 | 2 | 4 | .8 | | | | 4 | | | | 1 | | | 1 |
| C sp | 3 | | | | | 1 | .6 | | .7 | 1 | | 2 | 3 | | | 1 | .7 | 1 | | | | 2 | 1 | 2 | | .5 | 6 | | | | .8 |
| Ehrenbergina trigona | | | | .7 | | | .6 | | .7 | 2 | | | | | | 1 | 2 | 2 | 1 | | | | .6 | 2 | 1 | 1 | 1 | 1 | | 1 | 3 |
| Eponides pusillus | | | | | | | | 1 | .7 | | | | | | | | | | | | | | | | | | | | | | |
| E. tumidulus | 1 | | | | | | 1 | 1 | | | | | | | | 1 | | 1 | | | | | | | | | | | | | |
| E. umbonatus and variants | 3 | 5 | 6 | 3 | | 8 | 10 | 11 | 6 | 11 | 5 | 4 | 6 | 2 | 5 | 14 | 4 | 2 | 6 | 6 | 4 | 15 | 7 | 10 | 9 | 9 | 6 | 5 | 12 | 5 | 9 |
| Glomospira cf gordialis | | 1 | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | |
| Gyroidina lamarckiana | | | | | | 1 | | | | | | 2 | | | | | | | | | | | | | | | | 2 | | 3 | |
| G. orbicularis | 1 | | 1 | .7 | 4 | | 1 | 3 | 2 | 6 | 1 | | | | | 1 | | | 2 | | | | | | | | | | 5 | 4 | |
| G. soldanii variant | | 1 | | | 2 | | .6 | | | 1 | 1 | 2 | 3 | 4 | 1 | 4 | 1 | | 1 | .8 | 5 | | .6 | 6 | 3 | | | 2 | 3 | | |
| Höglundina elegans | 1 | 8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eggerella bradyi | 2 | | 2 | | 4 | | 1 | 2 | 3 | 4 | 7 | 2 | 5 | 4 | 1 | 1 | 3 | 1 | 6 | 2 | 2 | 2 | 3 | 2 | 5 | 3 | 6 | 2 | 3 | | |
| Laticarinina pauperata | | 3 | 1 | | | 1 | | | | | | | | 1 | 1 | 1 | .7 | | | | | 2 | | | | | | | | | .8 |
| Miliolids | | 4 | 2 | | | 5 | 1 | | 1 | | | | 1 | | | | 1 | 3 | 4 | | | | | | 1 | | | | | 1 | |
| Nonion barleeanum | 4 | 4 | 6 | 8 | 2 | | | | | 1 | | | | | | | | | 1 | | | 2 | .6 | | 2 | 4 | 6 | 1 | 2 | 3 | .8 |
| N. formosum | 3 | 1 | | 4 | 2 | 3 | | | | | 4 | 2 | 1 | | 2 | | .7 | 2 | | 2 | 4 | | 1 | | 1 | 2 | .6 | | | | |
| N. germanicum | 5 | 5 | 1 | .7 | | 1 | | 1 | .7 | | 1 | 2 | 7 | 14 | 6 | 6 | 7 | 12 | 12 | 18 | 16 | 4 | 1 | 6 | 1 | .5 | 15 | 36 | 13 | 17 | 17 |
| N. pompilioides | 5 | 1 | 6 | 9 | 2 | 1 | 10 | 1 | 13 | 1 | 3 | | 3 | | | 1 | 4 | 5 | 4 | 3 | 5 | 7 | 9 | 9 | 7 | 12 | 4 | 3 | 2 | 3 | 2 |
| Nonionella atlantica | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Osangularia cultur | | 1 | | | | | | | .7 | | | | | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 4 | 11 | 9 | 7 | 5 | 1 | 3 | | 6 | 6 | 4 | 2 | 5 | 6 | 6 | 5 | 3 | 5 | 5 | 4 | 7 | 7 | 5 | 10 | 7 | 2 | 6 | 4 | 3 | 7 | 3 |
| Pleurostomella acuminata | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | 3 | | |
| Epistominella exigua | 8 | 3 | | 4 | 4 | 3 | 3 | 8 | 5 | 4 | 1 | 2 | 3 | | 3 | 3 | 7 | 1 | 7 | 2 | | | 10 | 6 | 9 | 8 | .6 | 1 | | 5 | 3 |
| E. umbonifera | 1 | 2 | 1 | | 2 | | .6 | 2 | | | 1 | 6 | 5 | | 2 | 2 | 1 | 3 | | .8 | 4 | 2 | | | 1 | | | | | | |
| Pullenia bulloides | 12 | 7 | 8 | 12 | 12 | 14 | 16 | 18 | 24 | 19 | 12 | 12 | 8 | 16 | 7 | 5 | 11 | 12 | 13 | 15 | 9 | 7 | 12 | 8 | 24 | 13 | 8 | 3 | 10 | 16 | 16 |
| P quinqueloba | 5 | 3 | 4 | 3 | 5 | | 1 | 1 | | | 1 | | 4 | 4 | | 4 | 2 | 1 | 3 | .8 | 5 | 15 | 3 | 6 | 1 | | 2 | 2 | 7 | 1 | |
| P sp | 6 | 3 | 4 | 1 | | 1 | .6 | | | | | | 1 | | | 1 | .7 | 4 | 1 | 3 | 4 | | 1 | | 1 | .5 | 1 | | 2 | 1 | 2 |
| Pyrgo murrhina | 5 | 4 | 5 | 4 | 4 | 1 | 2 | 4 | 4 | 4 | 1 | 2 | 1 | 4 | 3 | 6 | 4 | 5 | 1 | .8 | | 4 | 3 | 2 | 1 | 1 | .6 | 2 | | | 6 |
| P oblonga | | | 1 | 1 | 2 | | | | | | 1 | | | | | | 1 | | | | | | | | | 2 | .6 | | 2 | | .8 |
| Rotamorphina laevigata | | | | | | | .6 | | | | | | | | | | | | | | | | | | | | | | | | |
| Quinqueloculina venusta | 3 | 3 | 1 | 1 | 5 | 1 | | | 1 | 1 | | | 3 | 1 | 3 | 1 | | 1 | 2 | 3 | 5 | 4 | 3 | 4 | 2 | 1 | 1 | 2 | 5 | | 2 |
| Q. cf weaveri | 4 | 4 | 4 | .7 | 2 | | | | 2 | 3 | 3 | 4 | | 2 | 2 | | .7 | 4 | 1 | | 4 | 7 | .6 | 4 | | .5 | 2 | 1 | | 1 | |
| Robulus | | 1 | | | | | .6 | | | | | | | | | | 1 | | 1 | | 2 | | | 2 | | | 1 | 1 | | 1 | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | | .7 | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | 2 | 3 | | | 2 | 5 | 1 | | | | | 8 | 3 | | | | | | 1 | | | | | | | | | | | | |
| Spiroloculina sp. | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Textularia australis | | | | | | | | | | | 4 | | | 1 | 1 | | | 1 | 1 | .8 | | | | 2 | 1 | | | | | | .8 |
| Triloculina tricarinata | | | | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Uvigerina hollicki | 6 | 7 | 11 | 26 | 12 | | 18 | 18 | 14 | 9 | 7 | 4 | | 2 | 1 | 8 | 23 | 5 | | 27 | | 2 | 29 | | 6 | 8 | 10 | 1 | 13 | 13 | 20 |
| Valvulineria humilis | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina advena | 1 | | 2 | | | 10 | 1 | 1 | 1 | | | | 10 | 4 | | | | | | | 2 | | | | | | .6 | | 2 | 1 | .8 |
| V. bradyi | 1 | | | | | | | 2 | | | | | | | | | | | 2 | .8 | | | 1 | | | | | | 3 | 3 | |
| V complanata | 1 | | 2 | | | | | | .7 | | 1 | | | | 1 | | .7 | | | | | | 1 | | | .5 | | | | | |

a uniform mud throughout and it is possible that it is a reliable one for studies of chronology.

**Core 238.** There are essentially no Foraminifera in the upper 380 cm. in this core; this apparently is due to solution since occasional fragments were observed. The majority of the samples show intense solution, but there are many lenses containing relatively complete specimens and large populations, as at 675 cm. There are two specimens of *Pulleniatina obliqu-*

*iloculata* and one of *Globorotalia truncatulinoides* at 351 cm.

At 420 cm. *Globorotalia* sp. 2 is present and occurs in most of the lower samples. The presence of this species suggests that the material is fossil, probably late Miocene or perhaps a little younger. One specimen of *G. multicamerata* occurs at 660 cm. *Cassidulina reflexa* is present between 1030 and 1084 cm. *Globigerina altispira* and *G. venezuelana* occur at 1090 cm. These latter forms are established Miocene and Oligocene fossils. It is of interest that neither *Globorotalia tumida* nor *G. menardii* is recorded from this core.

TABLE 16. Occurrences of Foraminifera in selected samples from Core 243 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 243 | DEPTH-3,740 M. | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 4 | 7 | 8 | 13 | 18 | 23 | 28 | 33 | 36 | 41 | 46 | 51 | 56 | 58 | 61 | 63 | 65 | 70 | 75 | 80 | 83 | 85 | 88 | 93 | 97 | 100 |
| CM. FROM TOP OF CORE | 1.5-2 | 29.5-30 | 59.5-60 | 69.5-70 | 119.5-120 | 169.5-170 | 219.5-220 | 269.5-270 | 319.5-320 | 349.5-350 | 399.5-400 | 449.5-460 | 499.5-500 | 549.5-550 | 569.5-570 | 599.5-600 | 619.5-620 | 639.5-640 | 689.5-690 | 739.5-740 | 789.5-790 | 819.5-820 | 841-841.5 | 869.5-870 | 919.5-920 | 959.5-960 | 989.5-990 |
| PLANKTONIC POPULATION | 30,100 | 55,400 | 23,200 | 112,400 | 27,900 | 30,200 | 20,900 | 22,100 | 22,700 | 18,300 | 37,100 | 47,900 | 12,300 | 7,900 | 16,800 | 58,100 | 30,000 | 40,000 | 30,600 | 26,200 | 48,500 | 10,600 | 8,700 | 19,400 | 23,400 | 8,200 | 16,400 |
| Candeina nitida | | | | | | | | | | | | | | | | | | | | | | | | | | .4 | |
| Globigerina bulloides | 2 | | 7 | 5 | 6 | | 3 | 6 | 7 | 12 | 9 | 12 | 5 | 5 | 6 | 9 | 1 | 4 | 3 | 9 | 4 | 3 | 3 | 7 | 9 | 1 | 2 |
| G digitata | | | | | | | | | | | | | | | .4 | | | | | | | .3 | | | | .4 | |
| G eggeri | 2 | 5 | 9 | 8 | 26 | 48 | 28 | 25 | 26 | 24 | 25 | 18 | 13 | 20 | 31 | 17 | 10 | 10 | 5 | 9 | 3 | 16 | 13 | 29 | 28 | 24 | 33 |
| G hexagona | | | | | | | | | | | | | | | | | | | | | | 2 | 4 | 1 | 1 | .8 | 4 |
| G inflata | .2 | .2 | | | 4 | 6 | 2 | 1 | 1 | 3 | 2 | .8 | .5 | .8 | | 3 | .4 | .6 | | 1 | .3 | 5 | 8 | 20 | 12 | 5 | 8 |
| G pachyderma | | .2 | 1 | .2 | | | | | .6 | | | | | | .8 | | | | | | | | | .7 | | | |
| G. quinqueloba | | 2 | .8 | 2 | | | | | .6 | | | | | | .4 | | | | | | 1 | .6 | | | .3 | | .4 |
| Globigerinella aequilateralis | 1 | 2 | 4 | 1 | | .8 | 1 | .6 | 1 | 2 | 2 | 1 | .5 | | .8 | 1 | 3 | 1 | 2 | .2 | 3 | 4 | | 2 | .6 | 2 | 2 |
| Globigerinita glutinata | 9 | 17 | 12 | 12 | 11 | 3 | 7 | 10 | 13 | 12 | 4 | 11 | 1 | 3 | 8 | 14 | 8 | 7 | 10 | 7 | 10 | 2 | 5 | 6 | 11 | 6 | 8 |
| Globigerinoides conglobata | .2 | | | | | | | .6 | R | .3 | .7 | .5 | | | | R | 3 | R | R | .2 | 2 | .3 | R | .3 | .6 | 2 | .4 |
| G rubra | 40 | 47 | 28 | 41 | 24 | 8 | 22 | 22 | 22 | 18 | 20 | 26 | 29 | 6 | 13 | 31 | 37 | 20 | 36 | 19 | 38 | 31 | 22 | 14 | 19 | 28 | 21 |
| G sacculifera | 35 | 17 | 22 | 14 | 17 | 17 | 22 | 15 | 14 | 13 | 17 | 11 | 33 | 14 | 12 | 9 | 12 | 12 | 14 | 16 | 29 | 24 | 16 | 7 | 10 | 16 | 7 |
| Globorotalia hirsuta | | .5 | .3 | | 1 | | | .6 | .6 | .7 | .7 | .3 | | .8 | | .2 | | | | | | .6 | | | | | |
| G menardii | 4 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → | .6 | | | | | |
| G. menardii-tumida group | | 3 | 2 | | 1 | | | | | R | | | | | | R | 2 | 22 | 19 | 18 | 6 | | | | | | .4 |
| G punctulata | | .2 | 1 | 2 | 1 | 2 | .3 | 1 | 2 | 1 | 1 | .3 | 1 | 2 | 4 | 4 | 4 | | 1 | 3 | .3 | 1 | 1 | 1 | .3 | 2 | 2 |
| G. scitula | | | .6 | | | | | | | | | | | | | | .8 | | | | | | | | | | .4 |
| G. truncatulinoides | .4 | 3 | 7 | 8 | 9 | 15 | 14 | 19 | 9 | 13 | 14 | 14 | 10 | 34 | 11 | 6 | 5 | 14 | 3 | 11 | .5 | 8 | 15 | 12 | 7 | 11 | 12 |
| G. tumida | 2 | — | — | — | → | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | .4 | .2 | .3 | .7 | | .4 | .6 | .3 | .3 | .7 | .3 | .5 | .5 | R | 2 | .2 | 4 | .3 | .4 | .5 | .5 | 1 | .4 | .7 | .3 | 1 | .8 |
| Pulleniatina obliquiloculata | 4 | 3 | 5 | 6 | | | | | 1 | .3 | 3 | 5 | 6 | 15 | 11 | 7 | 11 | 8 | 6 | 7 | 3 | 2 | 12 | | | | |
| Sphaeroidinella dehiscens | | | | | | | | | | | | | | | | | | | | | | .3 | | | | | |
| BENTHONIC POPULATION | 30 | 30 | 15 | 35 | 70 | 85 | 50 | 45 | 30 | 46 | 70 | 30 | 35 | 70 | 25 | 40 | 20 | 45 | 35 | 45 | 30 | 20 | 15 | 40 | 40 | 20 | 30 |
| Anomalina sp. | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | |
| Bolivina pseudopunctata | | | | 3 | 3 | 1 | | | | 2 | | | | | | | | | | | | | | | | | |
| Bulimina alazanensis | | 3 | | | | 4 | | | | | | | | | | | | | | | | 5 | 7 | | | 6 | |
| Cassidulina carinata | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | - |
| C. crassa | | | | | 1 | | 2 | | 3 | | | | | | | | | | | | | | | | | | |
| C. subglobosa | 14 | 10 | 7 | 9 | 6 | 5 | 2 | | 3 | 2 | 3 | 11 | 25 | 3 | 8 | 12 | 18 | 16 | 25 | 11 | 10 | 5 | | | | | 3 |
| Chilostomella oolina | | | | | | | 4 | 7 | 16 | 15 | 15 | | 3 | | | | | | | | | 53 | | 5 | 5 | | 3 |
| Cibicides robertsonianus | 24 | | | 9 | 2 | | 2 | 10 | | 2 | 4 | | 5 | | | 3 | 13 | | 12 | 10 | 7 | 5 | 21 | | 6 | | 6 |
| C. sp. | | 3 | 7 | 3 | | | | | | | 1 | 4 | | | | | | | | 2 | | | 7 | | | | |
| Ehrenbergina undulata | | | | 6 | | | | | | | | | | | | | | | | | | | | | | | |
| Eponides polius | | | | | | | | | | 2 | | | | | | | | 2 | | | | | | | | | |
| E. pusillus | | | | | 1 | | | 2 | | | | | | | | | | | | | | | | | | | |
| E. tumidulus | | | 7 | | | | | | | | 1 | | | | | | | | | | | | | | | | |
| E. umbonatus and variants | | | 21 | 9 | 13 | 7 | 10 | 5 | 3 | 6 | 3 | | 16 | 11 | 8 | 3 | 4 | 21 | 6 | | 17 | | 14 | 5 | 10 | 12 | 18 |
| Gyroidina lamarckiana | | | | | | | | | 3 | | | | | | | | | 2 | | | | | | | | | |
| G. orbicularis | | 7 | 7 | 3 | | | | | | | 4 | | | | | | | | | | | | | | | | |
| G. soldanii variant | | | | 3 | 1 | 1 | | | | | | | | | | 3 | | | | 2 | 7 | | | | 3 | | |
| Hoglundina elegans | | 7 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eggerella bradyi | 3 | | 7 | | | 1 | 4 | | 7 | | 8 | | | 4 | 4 | | | 2 | | 2 | | 5 | 7 | 3 | 3 | | |
| Laticarinina pauperata | | 3 | | 3 | | | | | | | | | | | | | 4 | | | | 3 | | | | | | |
| Nonion barleeanum | | | | | 9 | 8 | 4 | 16 | 10 | 9 | 13 | 18 | | 1 | 4 | 14 | 9 | 9 | 6 | 11 | 3 | 9 | 7 | 30 | 3 | 11 | 7 |
| N. formosum | 3 | | | | | | 2 | 2 | 3 | | 3 | 4 | | | | 5 | | | 6 | | | | | | | | |
| N. germanicum | 14 | 17 | 14 | 18 | 3 | 2 | 6 | 7 | 16 | 4 | 11 | 7 | | 7 | 20 | 22 | | | | | | | 7 | 3 | | | |
| N pompilioides | | | | | 6 | 12 | 15 | 16 | 13 | 6 | 3 | 18 | 3 | 7 | 8 | 8 | 18 | 5 | 3 | 4 | | | 14 | 3 | 16 | | 7 |
| Planulina wuellerstorfi | 17 | 14 | | 6 | 9 | 13 | 10 | 7 | 7 | 9 | 13 | 7 | 17 | 3 | 4 | 12 | 4 | 11 | 6 | 4 | 10 | 5 | | | 13 | 22 | 18 |
| Plectina apicularis | 7 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Epistominella exigua | | | | 3 | 3 | 5 | 4 | 5 | 3 | 4 | | 7 | | 21 | 20 | | | 2 | 8 | 9 | 3 | | | | 8 | 11 | 3 |
| E. umbonifera | 3 | 3 | | 3 | | | | | | | 1 | 4 | 3 | 1 | | | | | | | | | | | | 11 | |
| Pullenia bulloides | 3 | 3 | 7 | 3 | 20 | 14 | 15 | 16 | | 45 | 3 | 4 | 5 | 6 | 8 | 3 | 9 | 16 | 6 | 11 | 3 | | | 8 | 6 | 11 | 11 |
| P. quinqueloba | | 10 | 14 | | 1 | 1 | 2 | | 3 | 2 | 1 | 7 | 3 | 4 | | 3 | 14 | | 6 | 2 | 7 | | | 8 | | | 3 |
| P. sp. | | | | | | | 2 | | | | | 4 | | | | | | 2 | | | 7 | 5 | | 3 | 5 | | |
| Pyrgo murrhina | | | | 3 | 3 | 5 | | | | 9 | 6 | 4 | 5 | 3 | 8 | | 4 | | 8 | 4 | 3 | | | 8 | 3 | 11 | 11 |
| P. oblonga | | | | | 3 | 2 | 4 | | | | | | 3 | 4 | | | | | | | 7 | 5 | | 3 | | | |
| Quinqueloculina venusta | 10 | 7 | | 3 | | 1 | 6 | | | | 1 | 4 | | 4 | | | | 2 | | 2 | 3 | | | | 5 | 6 | 7 |
| Q cf weaveri | | 10 | 7 | 6 | | | | | | | 1 | | | | | | | 2 | 8 | | | | 7 | | | | |
| Robulus | | | | | | | | | | | | | 3 | | | | | | | | | | | | | | 3 |
| Siphotextularia rolshauseni | | | | 3 | | | | 2 | | | | | 3 | | | 3 | | | | | | | | 5 | | | |
| Uvigerina hollicki | | | | 3 | 7 | 7 | 4 | | | 4 | | | | 12 | 4 | 8 | | 2 | | 21 | 3 | | | 3 | | | |
| Virgulina advena | | | | 3 | 3 | 5 | | 5 | 7 | 9 | 3 | | 5 | 4 | 4 | | | 5 | | 2 | 3 | | | 3 | 5 | | |
| V bradyi | | | | | 3 | 2 | | | | | | | | 1 | | | | | | | | 5 | 7 | 12 | | | |

It does not appear desirable to attempt to interpret the latitude affinities of the faunas, even though most of the modern forms are present throughout the core. The section between 450 and about 750 cm. may contain a somewhat warmer-water fauna than lower layers.

**Core 239.** This is a short core, 176.5 cm. long, and was collected from 7490 m. depth. The top sample furnished, at 4—4.5 cm., is the only one containing Foraminifera and these are mostly juveniles. The fauna appears to be a somewhat mixed assemblage and not particularly normal for the latitude. No surface sample was furnished the writers.

**Core 242.** The top sample of this core contains a fauna differing from the surface sample collected at the same station in containing *Globigerina inflata, G. pachyderma,* and *Globorotalia truncatulinoides.* It is interpreted as showing somewhat higher-latitude affinities than its low-latitude position. The presence of *Nonionella atlantica* in the top sample is very questionable evidence of displacement.

The interpretation of faunal sequences in this core is extremely difficult; the interpretation suggested on Figure 24 is very tentative and may be over-simplified. There are at least five shifts from tropical to a higher latitude assemblage. Most of the higher latitude assemblages are in reality a mixed low and mid-latitude fauna.

*Globorotalia tumida* extends to 30 cm.

**Core 243.** This core shows only two apparent shifts from low-latitude to mid-latitude faunas in almost 10 m. of length. The inter-

TABLE 17. Occurrences of Foraminifera in selected samples from Core 246 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE. 246 | DEPTH- 3,210 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 4 | 6 | 8 | 10 | 11 | 16 | 19 | 22 | 26 | 30 | 32 | 34 | 36 | 37 | 40 | 43 | 46 | 48 | 50 | 52 | 56 | 60 | 62 | 65 | 69 | 73 | 76 | 77 | 79 | 81 | 82 | 88 |
| CM. FROM TOP OF CORE | 1.5-2 | 29.5-30 | 49.5-50 | 69.5-70 | 89.5-90 | 99.5-100 | 149.5-150 | 178.5-179 | 209.5-210 | 248-248.5 | 289.5-290 | 309.5-310 | 329.5-330 | 349.5-350 | 359.5-360 | 389.5-390 | 418-418.5 | 449.5-450 | 469.5-470 | 489.5-490 | 509.5-510 | 549.5-550 | 589.5-590 | 609.5-610 | 639.5-640 | 679.5-680 | 719.5-720 | 749.5-750 | 759.5-760 | 779.5-780 | 799.5-800 | 810.5-811 | 869.5-870 |
| PLANKTONIC POPULATION | 34,300 | 3,100 | 10,200 | 10,200 | 25,700 | 16,300 | 18,600 | 53,600 | 29,500 | 20,000 | 14,000 | 23,200 | 21,200 | 11,500 | 51,200 | 54,500 | 15,000 | 3,800 | 71,300 | 12,200 | 29,000 | 15,600 | 27,300 | 45,700 | 67,600 | 69,750 | 22,500 | 21,000 | 21,600 | 30,200 | 26,100 | 32,500 | 9,700 |
| Candeina nitida | | | .6 | | | | | | | | | | | .6 | | | | | | | | .4 | | | | | | | | | | | |
| Globigerina bulloides | 4 | 2 | 4 | 10 | 3 | 4 | 8 | 10 | 11 | 4 | 9 | 5 | 5 | 5 | 4 | 2 | 1 | 2 | 1 | 4 | 18 | 8 | 8 | 9 | 6 | 10 | 10 | 6 | 4 | 15 | 7 | 10 | 5 |
| G. digitata | | | | | .2 | | | | | | | | | .6 | .2 | | | | | .3 | | | | | | | | | | | | | |
| G. eggeri | 2 | 4 | 7 | 19 | 23 | 26 | 23 | 23 | 19 | 16 | 20 | 19 | 10 | 6 | 9 | 8 | 7 | 3 | 9 | 17 | 22 | 17 | 29 | 11 | 15 | 21 | 16 | 3 | | 19 | 15 | 9 | 5 |
| G. hexagona | | | | | | | | | | | | .3 | 1 | 2 | | .5 | 2 | 3 | 4 | 2 | | | | | | | 1 | .3 | .6 | | | | |
| G. inflata | | | .3 | 3 | .5 | 4 | 2 | 2 | .4 | .5 | .5 | 2 | .6 | | 1 | .2 | | | .8 | 4 | 13 | 5 | 2 | .8 | 2 | 2 | 1 | .3 | | .2 | 5 | .6 | .3 |
| G. pachyderma | | | | 1 | .2 | .6 | .7 | .5 | 1 | .2 | .2 | | | | | .5 | | | | .3 | .2 | | .5 | .6 | | | | | .6 | .4 | | | .7 |
| G. quinqueloba | | | .6 | .6 | .7 | .6 | | .5 | .4 | .3 | .5 | | 2 | | | | | 1 | | | .6 | | | | | | | | .3 | | .5 | .6 | |
| G. sp. 1 | | | .6 | | | | .3 | | .4 | | | | 1 | | | | | .7 | | | | | | 1 | | | | | .3 | | .5 | 1 | |
| Globigerinella aequilateralis | 2 | 3 | 5 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 4 | 2 | 3 | 3 | 1 | 3 | 3 | 2 | 2 | 2 | 4 | 3 | 3 | .7 | 2 | 2 | 2 | 1 | 2 | 3 | .3 |
| Globigerinita glutinata | 5 | 7 | 7 | 7 | 3 | 8 | 6 | 6 | 7 | 8 | | 12 | 13 | 14 | 9 | 10 | 5 | 8 | 9 | 4 | 7 | 14 | 7 | 6 | 6 | 9 | 9 | 10 | 9 | 12 | 20 | 20 | 8 |
| Globigerinoides conglobata | 1 | | .6 | | .7 | | | .2 | .4 | .2 | | .5 | | .3 | | | 1 | 1 | 1 | | .2 | | .5 | .8 | | .2 | | 2 | 1 | | | | 1 |
| G. rubra | 38 | 34 | 40 | 31 | 24 | 26 | 29 | 29 | 29 | 32 | 24 | 24 | 32 | 38 | 31 | 44 | 31 | 38 | 34 | 27 | 18 | 31 | 18 | 34 | 35 | 30 | 32 | 36 | 46 | 29 | 27 | 24 | 40 |
| G. sacculifera | 32 | 27 | 19 | 18 | 22 | 15 | 14 | 15 | 12 | 16 | 12 | 14 | 17 | 12 | 11 | 10 | 21 | 25 | 22 | 13 | 6 | 10 | 9 | 11 | 15 | 10 | 15 | 17 | 19 | 8 | 8 | 10 | 17 |
| Globorotalia hirsuta | | | | | | | .2 | .2 | | .3 | | | | | | | | | | .3 | | .2 | | | | | | .3 | | | | | |
| G. menardii | 7 → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. menardii-tumida group | 1 | 10 | .6 | | 2 | | | | | | | | .3 | 3 | 15 | 11 | 15 | 8 | 5 | .5 | .2 | .2 | 13 | 10 | 8 | 8 | 6 | 11 | 6 | 7 | 7 | 7 | 6 |
| G. punctulata | .6 | 1 | .6 | 2 | 4 | 2 | 4 | 1 | 1 | 1 | 1 | 4 | 5 | 3 | .8 | 2 | 5 | 1 | 2 | 2 | 1 | .2 | 2 | .6 | .5 | .4 | 1 | 1 | 1 | .6 | 1 | .6 | 1 |
| G. scitula | 2 | 2 | 1 | 2 | | .2 | .7 | .5 | .4 | .6 | .7 | .8 | 2 | .3 | 1 | .7 | | .3 | .8 | .5 | 1 | 2 | .7 | .8 | .7 | .6 | .6 | | 1 | .6 | .5 | | .7 |
| G. truncatulinoides | .6 | 2 | 5 | 5 | 11 | 11 | 11 | 11 | 11 | 11 | 12 | 10 | 6 | 7 | 9 | 4 | 7 | 1 | 5 | 13 | 10 | 9 | 4 | 4 | 4 | 5 | 3 | 5 | 2 | 3 | 1 | 7 | 11 |
| G. tumida | 2 → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | .4 | .4 | .3 | | .5 | .2 | | | | .2 | | .5 | .3 | .3 | .2 | .2 | | 1 | | .5 | .6 | .6 | .2 | .6 | | | | .6 | .3 | | | .6 | |
| Pulleniatina obliquiloculata | 4 | 6 | 8 | 2 | 2 | | | .2 | 6 | 5 | | 7 | 3 | 5 | 4 | 4 | 5 | 5 | 5 | 8 | | | 1 | 5 | 3 | 2 | 3 | 5 | 6 | 5 | 5 | 8 | 4 |
| Sphaeroidina bulloides | | | | | | | | .2 | | | | .3 | | | | | | | | | | | | | .2 | | | | | | | | |
| Sphaeroidinella dehiscens | .2 | 2 | | | .5 | | | | | | | | | | | | | | .3 | | | | | | | | | | | | | | |
| BENTHONIC POPULATION | 90 | 90 | 40 | 60 | 160 | 200 | 105 | 180 | 110 | 60 | 200 | 190 | 100 | 80 | 150 | 90 | 130 | 130 | 80 | 80 | 170 | 130 | 120 | 100 | 90 | 270 | 50 | 60 | 40 | 110 | 60 | 70 | 90 |
| Anomalina sp. | | | | | .6 | | 1 | | | | | | | | | | .8 | | | | | | 1 | 1 | | | | | | | 2 | | |
| Bolivina cf. minuta | | 1 | | | | | | | 1 | | | | | | | | | 2 | 1 | | | | | | | | | | | | | | |
| B. pseudopunctata | | | | 4 | 1 | | | .6 | 2 | 2 | 1 | | | | 1 | 1 | | | | 1 | | | 2 | | | | | | | | | | |
| Bulimina alazanensis | 2 | | | | | | | 1 | 1 | | | | | | .7 | | .8 | 2 | 3 | 4 | | | | | 1 | | 2 | | 3 | | | | |
| B. translucens | 16 | 6 | 8 | 14 | 4 | 1 | 14 | 4 | 2 | 12 | 4 | 4 | 4 | 5 | 2 | 2 | 2 | 19 | 10 | 25 | 2 | 9 | 5 | 5 | 5 | 3 | 22 | 27 | 16 | 8 | 8 | 7 | 3 |
| Cassidulina carinata | | | | | | | | | | | | 2 | 6 | | 3 | 1 | | 2 | | | | | | | | | | | | | | | |
| C. crassa | | | | | | | | | | | .5 | | | | | | | | 1 | | | | | | | | | | | | | | |
| C. subglobosa | 8 | 8 | 6 | 5 | 7 | 4 | 5 | 4 | 15 | 3 | 11 | 7 | 16 | 14 | 8 | 11 | 8 | 6 | 2 | 8 | 1 | 16 | 4 | 10 | 19 | 10 | 11 | 12 | 14 | 12 | 9 | 8 | 8 |
| Chilostomella oolina | | | | | | | 2 | 1 | 1 | | | | | | | | | | | | 5 | .8 | | | | | | | | | | 1 | |
| Cibicides kullenbergi | 9 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. robertsonianus | | | | | | | 3 | 2 | 2 | | | 2 | | 1 | .7 | 4 | 3 | 4 | 1 | 1 | .2 | .8 | | 1 | | 2 | 4 | | 6 | | | 1 | |
| C. sp. | | | | | | | 2 | 1 | | | | 2 | 1 | | | | | .8 | 1 | | .6 | | | 2 | 1 | 2 | | 3 | 8 | 2 | 8 | 3 | 1 |
| Ehrenbergina undulata | | | | | | | | | | | | | | | | | | | | | | | 1 | | | .4 | | | | | | | |
| Eponides polius | 11 | 2 | 6 | 2 | .6 | | | | | | | | | | | | | 2 | 1 | | | | | | | | | | | | | | |
| E. pusillus | | | | 11 | 17 | 30 | 30 | 18 | 20 | 28 | 15 | 13 | 14 | 10 | 12 | 8 | 16 | 7 | 6 | 7 | 24 | 17 | 24 | 10 | 13 | 10 | 7 | 2 | 5 | 23 | 3 | 8 | 11 |
| E. tumidulus | 8 | 12 | | 2 | | | | 1 | 3 | | .5 | | | 3 | | | | | | | | | 1 | | | 2 | | | | | | | |
| E. umbonatus and variants | | 3 | 10 | | 4 | 5 | 5 | 8 | 5 | 5 | 4 | 8 | 5 | 5 | 6 | 7 | .8 | 8 | 6 | 1 | 3 | 3 | 10 | 1 | 1 | 1 | 6 | 5 | 5 | 2 | 4 | 3 | 3 |
| Glomospira charoides | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. cf. gordialis | 3 | 7 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Gyroidina lamarckiana | | | | | | | | | | | | .5 | | | | | | | | | | | | | | | | | | | | | |
| G. orbicularis | | 6 | 9 | 2 | 3 | 5 | 3 | 4 | 3 | | | 1 | 1 | 1 | 2 | | 2 | | 1 | 1 | 2 | | 3 | 1 | 1 | .7 | | | | | 2 | 1 | 1 |
| G. soldanii variant | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Höglundina elegans | 4 | 2 | | | | | | 2 | 4 | | | | | | | | | | | | | | | | | | | | | | | | |
| Eggerella bradyi | 1 | 3 | | 7 | | .5 | 1 | | | | 1 | 1 | | 3 | | 1 | .8 | .8 | 7 | 3 | 2 | .8 | 1 | 2 | 1 | | | 2 | | 4 | 5 | 1 | 1 |
| Laticarinina pauperata | 2 | 2 | 6 | | | | | | | | | | | | | | .8 | 2 | | | | | | | 1 | | | 2 | | | | | |
| Nonion barleeanum | | | | 2 | 3 | 3 | | 2 | 3 | 12 | 4 | 6 | 5 | 5 | 5 | | 8 | | 1 | 5 | 8 | 5 | 4 | 6 | 6 | 3 | 2 | | 3 | 7 | 5 | 11 | 3 |
| N. formosum | | | | | | | | | | 2 | | | | | | | | | | | | | | | 1 | | | | | | | | |
| N. germanicum | | | | 12 | 6 | 3 | 5 | 8 | 6 | 2 | 5 | 18 | 14 | | 3 | 1 | | .8 | | | | | | | | 2 | | | | 2 | | | 2 |
| N. pompilioides | | | 3 | 4 | 2 | 5 | 8 | 2 | 3 | | 1 | 2 | | | 1 | 1 | 2 | .8 | 1 | 1 | 4 | | 1 | 2 | | 1 | 2 | | 3 | 1 | 2 | 7 | 4 |
| Nummoloculina irregularis | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Osangularia cultur | 2 | 2 | | | .6 | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | |
| Patellina corrugata | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 4 | 3 | 8 | 5 | 9 | 5 | 3 | 3 | 5 | 7 | 4 | 9 | 7 | 12 | 10 | 11 | 5 | 4 | 7 | 16 | 7 | 8 | 6 | 14 | 7 | 4 | | 14 | 5 | 5 | 9 | 13 | 3 |
| Epistominella exigua | 4 | | 6 | 16 | 20 | 16 | 5 | 7 | 8 | 14 | 23 | 7 | 7 | 20 | 15 | 26 | 28 | 7 | 2 | 7 | 9 | 19 | 9 | | 15 | 22 | 11 | 2 | 8 | 3 | 12 | 14 | 37 |
| E. umbonifera | 2 | | | | | | 1 | 1 | 2 | | 1 | | 4 | | .7 | 2 | | 2 | 4 | | | 2 | | | 1 | | | | | | | | |
| Pullenia bulloides | | 2 | | 5 | 4 | 2 | 1 | 4 | 2 | | | 2 | | 2 | 3 | 1 | 2 | 8 | 6 | 2 | 4 | 3 | 7 | 12 | 1 | 7 | | | 8 | 6 | | 4 | 1 |
| P. quinqueloba | 4 | 6 | 8 | 2 | 6 | 2 | 3 | 15 | 6 | | 9 | 3 | 5 | 4 | 16 | 13 | 8 | 4 | 4 | 1 | 2 | 2 | 3 | 3 | 10 | 13 | 13 | 2 | 3 | 5 | 10 | | 5 |
| P. sp. | | | 6 | | | 1 | 2 | .6 | 1 | | 2 | .5 | | 4 | | 1 | 2 | | 2 | | 2 | .8 | 2 | 2 | | 1 | 2 | | 5 | 2 | 2 | | |
| Pyrgo murrhina | 1 | 1 | | | 2 | | 3 | 3 | 1 | | 3 | 3 | 4 | 6 | 6 | 1 | 2 | 3 | 8 | 7 | 7 | 2 | 5 | 15 | 2 | 4 | 2 | | 5 | 6 | 2 | 8 | 2 |
| P. oblonga | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Quinqueloculina venusta | 8 | 7 | 10 | 2 | 3 | 1 | | 2 | | 7 | 1 | .5 | 4 | 1 | 3 | 1 | .8 | 5 | 2 | 1 | | 2 | 1 | 2 | 3 | .7 | 2 | 2 | | 2 | 2 | | 2 |
| Q. cf. weaveri | 4 | 6 | 8 | | 2 | .5 | 2 | | 1 | | | .5 | 1 | 1 | 1 | 5 | 2 | 3 | 4 | 1 | 3 | | 1 | 1 | 1 | .7 | 2 | 3 | 5 | 1 | 6 | 7 | 1 |
| Robertina bradyi | | 4 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sigmoilina schlumbergeri | | | | | | | | | | | | .5 | | | | | | | 1 | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | | | | | | 1 | .6 | | | .5 | | 1 | | 1 | | | 2 | 4 | | 2 | 2 | 1 | 1 | | .4 | | | | 1 | | | 1 |
| Spiroloculina sp. | 1 | | | 2 | | | | | | | | | | | | | | .8 | 1 | | | .8 | | | | | | | 3 | | | | |
| Textularia australis | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 2 | | | | | | |
| Triloculina tricarinata | | 1 | | | | .5 | | .6 | | | 1 | | | | | | | | | | 1 | | | | 1 | | | | | | | | |
| Uvigerina hollicki | | 1 | | | 1 | 6 | | 2 | | | 3 | 5 | | 3 | 1 | | 5 | 2 | 2 | 5 | 8 | | 2 | | 7 | 5 | 9 | 25 | | 2 | | | 3 |
| Virgulina advena | | | | 4 | 1 | 4 | | | 1 | 3 | | 1 | 2 | | | | 2 | .8 | 1 | | | 2 | 2 | | | 2 | | | | 2 | | | 2 |
| V. bradyi | | | | | 1 | 1 | | | | | .5 | | | | | | | .8 | | | | 2 | 2 | 2 | | | | | | | | | |
| V. complanata | 1 | | | | 2 | 1 | 1 | .6 | 3 | 3 | 2 | 2 | 1 | 1 | 1 | 1 | .8 | .8 | 5 | 1 | 2 | 2 | 4 | 1 | | | 2 | | | 5 | 5 | 1 | 1 |
| V. sp. | | | | | | .5 | | | | | | | | | | | | | | | | | | | | | | | | | | | |

mediate faunas shown from 4—6 m. and between 8 and 9 m. are essentially mixed faunas. *Globorotalia tumida* extends to 120 cm.

**Core 246.** The top fauna is normal for the equatorial area in which this core was collected. There are at least three shifts to a more nor-

TABLE 18. Occurrences of Foraminifera in selected samples from Core 248 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 248 | | | | | | | | | | | | | | | | DEPTH-4,580M. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 7 | 10 | 12 | 14 | 15 | 16 | 19 | 25 | 27 | 31 | 33 | 38 | 40 | 43 | 45 | 47 | 52 | 69 | 84 | 85 | 89 | 91 | 92 | 94 | 97 | 98 | 101 |
| CM. FROM TOP OF CORE | 1.5-2 | 41.5-42 | 59.5-60 | 89.5-90 | 109.5-110 | 129.5-130 | 139.5-140 | 149.5-150 | 180.5-181 | 239.5-240 | 259.5-260 | 299.5-300 | 319.5-320 | 369.5-370 | 389.5-390 | 419.5-420 | 439.5-440 | 459.5-460 | 509.5-510 | 679.5-680 | 829.5-830 | 839.5-840 | 879.5-880 | 899.5-900 | 909.5-910 | 929.5-930 | 959.5-960 | 969.5-970 | 999.5-1000 |
| PLANKTONIC POPULATION | 890 | 3,200 | 25 | 5,000 | 500 | 15 | 4,500 | 310 | 3,600 | 800 | 50 | 15 | 45 | 15 | 70 | 15 | 55 | 80 | 55 | 10 | 0 | 0 | 35 | 55 | 5,760 | 11,200 | 175 | 1,725 | 1,140 |
| Globigerina bulloides | | 5 | 4 | 3 | .8 | | 3 | 4 | 3 | .5 | | 13 | 5 | | 7 | | | 11 | 14 | 10 | | | 3 | 41 | 12 | 8 | 10 | | |
| G. eggeri | 4 | 2 | 4 | 11 | 36 | 61 | 35 | 41 | 44 | 55 | 4 | 7 | 16 | 15 | 13 | 21 | 19 | 34 | 11 | 10 | | | | | | 4 | 5 | 53 | 55 |
| G. hexagona | | | | | | | | | .4 | | | | 2 | | 1 | | | | | | | | | | | .6 | | | |
| G. inflata | | | | | | | 2 | 2 | | .5 | 2 | | | | 1 | | | 1 | | | | | | | | | | 2 | .7 |
| G. pachyderma | | | | .3 | | | .7 | | | 2 | 2 | | | | | 7 | | | | | | | | | | | | | |
| G. sp 1 | | | | | | | | | | | | | | | | | | | | | | | 86 | 12 | 12 | | | | |
| Globigerinella aequilateralis | 4 | 3 | | 5 | 2 | 8 | .4 | | | | 2 | | 5 | | | 7 | | 1 | 7 | | | | | | 2 | 2 | .6 | | .7 |
| Globigerinita glutinata | 1 | 3 | | .3 | .4 | | .4 | | 1 | 1 | 10 | | 2 | | 3 | | 4 | 4 | | | | | | 16 | 47 | 35 | 15 | .5 | |
| Globigerinoides conglobata | .5 | | | .3 | | | .4 | .6 | | | 2 | | | | | 7 | | | | | | | | | | | | | .4 |
| G. rubra | 32 | 42 | 16 | 22 | 26 | 8 | 10 | 10 | 11 | 9 | 44 | 53 | 43 | 23 | 33 | 29 | 32 | 11 | 37 | 50 | | | 9 | 25 | 20 | 38 | 55 | 8 | 11 |
| G. sacculifera | 28 | 18 | 32 | 29 | 23 | 15 | 30 | 26 | 23 | 18 | 18 | 20 | 16 | 31 | 20 | 14 | 32 | 28 | 16 | 20 | | | | | | 7 | 4 | 20 | 16 |
| Globorotalia menardii | .5 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | → | | |
| G. menardii-tumida group | 4 | 18 | 20 | | .4 | | | | .4 | | | | 2 | 15 | 4 | 7 | | | 2 | 10 | | | 3 | 2 | 4 | 3 | 6 | | |
| G. punctulata | | | | 2 | 1 | | 2 | 2 | 3 | 2 | 4 | | | | 4 | | 2 | 4 | 2 | | | | | | | | | 3 | 6 |
| G. scitula | | 2 | 8 | | .4 | | | .3 | | | | | | | | | | | | | | | | 4 | 2 | 1 | 1 | | |
| G. truncatulinoides | 2 | .5 | 4 | 9 | 3 | | 16 | 14 | 15 | 11 | 10 | 7 | 5 | 15 | 9 | 7 | 9 | 5 | 11 | | | | | | | 1 | 4 | 12 | 11 |
| G. tumida | 14 | — | → | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | 1 | | | | | 8 | .7 | .6 | | .5 | | | | | | | | | | | | | | | 1 | | | .5 | |
| Pulleniatina obliquiloculata | 9 | 5 | 12 | 19 | 6 | | | | .4 | .5 | 2 | | 5 | | 3 | | 2 | 1 | 2 | | | | | | | 1 | | | |
| Sphaeroidinella dehiscens | .5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| BENTHONIC POPULATION | 4 | 12 | 2 | 50 | 7 | 0 | 95 | 6 | 60 | 35 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | 1 | 1 | 5 | 6 | 125 | 980 | 3,500 | 3,350 | 2,560 | 70 | 35 |
| Amphistegina lessonii | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | | |
| Angulogerina selseyensis | | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | 1 | |
| Bolivina globulosa | | | | | | | | | | | | | | | | | | | | | | | | 3 | | 6 | | | |
| B. cf. minuta | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | |
| B. paula | | | | | | | | | | | | | | | | | | | | | | | 10 | 24 | 5 | 35 | 30 | 6 | |
| B. pseudoplicata | | | | | | | | | | | | | | | | | | | | | | | 3 | 5 | 10 | | 8 | 4 | 3 |
| B. pseudopunctata | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | |
| B. pulchella | | | | | | | | | | | | | | | | | | | | | | | | 2 | 1 | 4 | | | |
| B. subaenariensis | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 | | |
| B. tortuosa | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 5 | | |
| B. sps. | | | | | | | | | | | | | | | | | | | | | | | 16 | 23 | | | | | |
| Bulimina translucens | | | | | | | | | | | | | | | | | | | | | | | | 2 | 2 | 1 | 1 | | |
| Cassidulina carinata | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | 2 | | |
| C. subglobosa | | 17 | 50 | 21 | 43 | | 4 | | 5 | 3 | | | | | | | 100 | | | | | | | 5 | | 3 | 2 | 6 | 3 |
| Cassidulinoides mexicana | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | |
| Chilostomella oolina | | | | | | | | | | | | | | | | | | | | | | | 6 | | | | | | |
| Cibicides cf. refulgens | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | |
| C. robertsonianus | | | | 2 | | | 1 | | 2 | | | | | | | | | | | | | | | | | | | | 3 |
| Cornuspira planorbis | | | | | | | | | | | | | | | | | | | | | 60 | 28 | 6 | 6 | 1 | | | | |
| Discorbis cf. columbiensis | | | | | | | | | | | | | | | | | | | | | | | 13 | 10 | 13 | 8 | 20 | | |
| D. williamsoni | | | | | | | | | | | | | | | | | | | | | | 14 | 16 | 5 | 5 | 5 | 1 | | |
| Eponides pusillus | | | | 4 | 14 | | 25 | 50 | 20 | 8 | | | | | | | | 14 | | | | | 2 | 5 | 2 | 3 | | 12 | 37 |
| E. umbonatus and variants | | 34 | | 6 | 14 | | 6 | | 18 | 30 | | | | | | | | 28 | | | | | 2 | | | | | 13 | 3 |
| Gyroidina lamarckiana | | 17 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. orbicularis | | | | | | | 1 | | 2 | | | | | | | | | | | | | | | | | | | | |
| Eggerella bradyi | | 8 | | 4 | 14 | | 5 | | 2 | | | | | | | | | | | | | | | | | | | 6 | |
| Miliolids | | | | | | | | | | | | | | | | | | | | | | | 11 | | 5 | 7 | 9 | | 8 |
| Nonion formosum | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 |
| N. pompilioides | 25 | | | 4 | | | 1 | | 2 | 3 | | | | | | | | | | | | | | | | | | | 3 |
| Nonionella sloanii | | | | | | | | | | | | | | | | | | | | | | 28 | 3 | 2 | | | | | |
| Ophthalmidium inconstans | | | | | | | | | | | | | | | | | | | | | | | 2 | | 3 | | | | |
| Patellina corrugata | | | | | | | | | | | | | | | | | | | | | 20 | | 3 | | | | | | |
| Planulina wuellerstorfi | 25 | | | 10 | | | 7 | | 8 | 10 | | | | | | | | | | | | | | 2 | | | | 6 | |
| Epistominella exigua | | 8 | | 17 | 14 | | 11 | 17 | 5 | 10 | | | | | | | | | 100 | 100 | | | | | 3 | 1 | 1 | 16 | 5 |
| E. umbonifera | 50 | 8 | | 8 | | | 1 | | | | | | | | | | | | | | | | | | | 1 | | 6 | |
| Pullenia bulloides | | | 50 | 4 | | | | | | | | | | | | | | 14 | | | | | | 2 | | | | 1 | 3 |
| P. quinqueloba | | 8 | | 12 | | | 23 | 17 | 27 | 30 | | | | | | | | 43 | | | | | | 5 | 2 | 2 | 2 | 14 | 19 |
| P. sp. | | | | | | | 7 | | 2 | 3 | | | | | | | | | | | | 14 | | | | | | 4 | 3 |
| Pyrgo murrhina | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | 1 | 3 |
| Rotamorphina laevigata | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | |
| Quinqueloculina cf. weaveri | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | | | 2 | | | 1 | | 3 | 3 | | | | | | | | | | | 20 | | | | | | | 3 | |
| Textularia australis | | | | 4 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Triloculina tricarinata | | | | | | | | | | | | | | | | | | | | | | 14 | | | 1 | | | | |
| Virgulina complanata | | | | | | | 2 | 17 | 5 | | | | | | | | | | | | | | | | | | | | 3 |
| V. mexicana | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | |
| V. tessellata | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | |
| V. sp. | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | 3 |

therly type fauna, separated by low-latitude assemblages. This core is uniform in appearance and is mostly a *Globigerina* ooze.

*Globorotalia tumida* extends to 90 cm. *Globigerina hexagona* occurs below 310 cm.

**Core 248.** This core contains a great deal of solution effects, as can be seen by examining the total populations. This reduces the reliability of the interpretations. There are only two clear-cut shifts to mid-latitude faunas in 830 cm., separated by intermediate or low-latitude assemblages.

From 830 to 1,000 cm. the fauna has been displaced from shoaler water, as indicated by

TABLE 19. Occurrences of Foraminifera in selected samples from Core 252 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 252 DEPTH-4,480 M.

| SAMPLE | 1 | 2 | 3 | 6 | 7 | 9 | 13 | 17 | 18 | 19 | 23 | 24 | 25 | 29 | 30 | 31 | 33 | 37 | 41 | 42 | 46 | 48 | 60 | 62 | 67 | 70 | 77 | 82 | 85 | 86 | 89 | 90 | 91 | 94 | 96 | 98 | 102 | 103 | 104 | 105 | 109 | 110 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 2.5-3 | 9.5-10 | 19.5-20 | 49.5-50 | 59.5-60 | 79.5-80 | 119.5-120 | 159.5-160 | 169.5-170 | 179.5-180 | 219.5-220 | 229.5-230 | 239.5-240 | 279.5-280 | 289.5-290 | 299.5-300 | 319.5-320 | 359.5-360 | 399.5-400 | 409.5-410 | 452-452.5 | 469.5-470 | 589.5-590 | 996.5-997 | 1075-1075.5 | 1116-1116.5 | 1259.5-1260 | 1284.5-1285 | 1299.5-1300 | 1304.5-1305 | 1319.5-1320 | 1344.5-1345 | 1354.5-1355 | 1365-1365.5 | 1375-1375.5 | 1384.5-1385 | 1404.5-1405 | 1409.5-1410 | 1414.5-1415 | 1419.5-1420 | 1429.5-1430 | 1435-1435.5 |
| PLANKTONIC POPULATION | 90 | 130 | 7 | 24 | 13 | 2,200 | 60 | 50 | 215 | | 5,000 | 48,750 | 625 | 4,200 | 55 | 2 | 550 | 130 | 30 | 12 | 75 | 7 | 220 | 310 | 2,100 | 2,200 | 105 | 23 | 1,300 | 7,500 | 75 | 9,100 | 750 | 3,700 | 2,400 | 2,300 | 75 | 2,400 | 230 | 1,700 | 183,000 | 1,600 |
| Globigerina bulloides | 1 | | | 12 | | | | 12 | 14 | | 9 | .5 | | | | | 1 | | 7 | | 3 | 14 | 1 | | .4 | | | | | 1 | | .7 | | .4 | .7 | .3 | | .4 | | | 2 | |
| G. digitata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | |
| G. eggeri | 25 | 50 | 14 | 4 | | 7 | 14 | 8 | 2 | | 10 | 10 | 57 | 23 | 20 | | 43 | 41 | 3 | 17 | 5 | | 23 | 23 | 18 | 15 | 16 | 13 | 16 | 10 | 4 | 5 | 18 | 9 | 34 | 50 | 74 | 52 | 33 | 18 | 5 | 24 |
| G. hexagona | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | | | | 1 | | .4 | | | | | | | | | | |
| G. inflata | | | | | | 1 | 2 | 2 | | | 6 | | | | | | | | | | | | | .7 | | | | | | | 4 | .4 | | 8 | 17 | 5 | 3 | .7 | 12 | 2 | | |
| G. pachyderma | | 2 | | | | | | | 1 | | 2 | | | | | | | | | | 3 | | .5 | | | | | | | | | | | | | .7 | 1 | 2 | | | | .5 |
| G. quinqueloba | 2 | | 14 | 25 | 54 | 3 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | .4 | | | | | | | | | .3 | |
| G. sp. 1 | 1 | | | | | | | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Globigerinella aequilateralis | 1 | | 14 | | | | | 4 | 2 | | | 2 | | .4 | | | | | 3 | | | | 1 | | 1 | .5 | | | .6 | 3 | | 8 | 2 | 3 | | 2 | | .4 | | | 7 | |
| Globigerinita glutinata | 11 | 28 | | 21 | | 2 | | 28 | 31 | | 13 | .8 | .6 | 11 | 6 | 50 | | 2 | 28 | 25 | 20 | 43 | 11 | | .8 | 8 | | | | 1 | | 8 | 1 | .4 | 1 | 1 | | | | 2 | 15 | |
| Globigerinoides conglobata | 4 | 5 | | | | 1 | | | | | | 3 | 1 | | | | | | 3 | | | | .5 | 2 | 2 | 10 | 1 | | .6 | 7 | | 8 | 2 | 3 | .7 | 1 | | 2 | | .5 | .3 | 2 |
| G. rubra | 10 | | | 21 | 15 | 20 | 31 | 40 | 40 | | 47 | 30 | 1 | 23 | 28 | 50 | 4 | 6 | 28 | 33 | 46 | 43 | 6 | .7 | 3 | 11 | 1 | | 9 | 12 | 1 | 20 | | 5 | .6 | 10 | | 16 | | 18 | 51 | 14 |
| G. sacculifera | 20 | 5 | 28 | 12 | | 50 | 41 | | 2 | | 16 | 44 | 28 | 20 | 33 | | 36 | 31 | 7 | 8 | 14 | | 3 | 2 | 14 | 17 | 3 | 26 | 14 | 28 | 1 | 32 | 16 | 22 | 11 | 13 | 1 | .5 | 3 | 18 | 10 | 17 |
| Globorotalia hirsuta | 1 | | | | | | | | | | | | | | | | | .8 | | | 1 | | | .7 | | 1 | | | | .6 | | | | | | .3 | | | | | | |
| G. menardii | 10 → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. menardii-tumida group | | | 28 | 4 | | | | 2 | 7 | | .6 | 2 | | | | | | | 13 | 17 | 3 | | 3 | 52 | 47 | 9 | 38 | 35 | 44 | 28 | 68 | 5 | 32 | | | | | | 49 | 23 | 6 | 26 |
| G. punctulata | 6 | 2 | | | | 2 | 7 | | | | .3 | .3 | 1 | 8 | 6 | | 3 | 5 | 3 | | | | 2 | .3 | .8 | | 11 | 9 | 3 | 1 | 13 | .4 | 2 | 6 | 3 | 1 | 11 | .4 | | .5 | | 3 |
| G. scitula | | | | | 15 | | | | 1 | | | | | .4 | 2 | | 1 | | | | | | | | | | | | | | | | | | .7 | | | | | | | |
| G. truncatulinoides | 2 | 9 | | | 8 | 11 | 5 | | | | 1 | 3 | 10 | 14 | | | 10 | 9 | | | 3 | | 8 | 5 | 2 | 3 | 4 | 4 | 3 | .6 | 3 | 1 | | 15 | 17 | 13 | 10 | 10 | | 8 | .7 | 1 |
| G. tumida | 1 → | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | 2 | | | | | | | | | | | .5 | | | | | | | | | | | | | .4 | 2 | | | | 1 | | .4 | | 1 | | 1 | | .7 | 2 | .5 | 3 | 1 |
| Pulleniatina obliquiloculata | 1 | | | | | | | | 1 | | .6 | 3 | | | | | | 5 | 3 | | | | 42 | 15 | 10 | 22 | 26 | 13 | 8 | 5 | 4 | 7 | 23 | 28 | | .7 | | | | 11 | 1 | 12 |
| [Sphaeroidina bulloides] | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| Sphaeroidinella dehiscens | | | | | 8 | | | | | | | | | | | | | | | | | | | | | | | | 1 | .6 | 1 | 1 | 2 | | | | | | | | | |
| BENTHONIC POPULATION | 8 | 9 | 2 | 6 | 3 | 20 | 3 | 35 | 115 | 155 | 115 | 260 | 15 | 20 | 2 | 0 | 20 | 30 | 11 | 2 | 60 | 6 | 60 | 35 | 35 | 35 | 35 | 1 | 60 | 165 | 25 | 60 | 45 | 35 | 55 | 65 | 25 | 50 | 65 | 40 | 165 | 40 |
| Amphistegina lessonii | | | | | | | | | 3 | .7 | 3 | 2 | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | |
| Angulogerina selseyensis | | | | | | | | | | 2 | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Anomalina sp. | | | | | | | | | | | | .8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |
| Bolivina globulosa | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. cf. minuta | | | | | | | | | | 1 | | .4 | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | |
| B. paula | 12 | | | 17 | 33 | | | 3 | 45 | 42 | 38 | 22 | | | | | | | 45 | 100 | 44 | 33 | 17 | | | | | | | | | | | | | | | | | | | |
| B. pseudoplicata | | | | 50 | | | | 3 | 9 | 3 | 3 | 3 | | | | | | | | | 10 | | 5 | | | 3 | | | | | | | | | | | | | | | | |
| B. pseudopunctata | | | | | | 28 | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. pulchella | | | | | | | | | | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. subaenariensis | | | | | | | | | 2 | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. tortuosa | | | | | | | | | 2 | 3 | 5 | 3 | | | | | | | | | 2 | 17 | 2 | | | | | | | | | | | | | | | | | | | |
| B. sps. | | | | | | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bulimina aculeata | | | | | | | | | 2 | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. alazanensis | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 18 | |
| B. exilis | | | | | | 9 | | | | | | | | | | | | | | | | | | | | 6 | | | | | | | | | | | | | | | | |
| B. marginata variant | | | | | | | | | | | | .4 | | | | | | | | | | | | | | 3 | | | | | | | | | | | | | | | | |
| B. mexicana | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. translucens | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |
| Cassidulina carinata | | | | | | | | | 5 | 3 | 6 | 3 | | | | | | | | | 3 | | 3 | | | | | | | | | | | | | | | | | | | |
| C. crassa | | | | | | | | | | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. curvata | | | | | | | | | | | 3 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. norcrossi australis | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. subglobosa | 25 | 11 | | | | 5 | | | 5 | 3 | 9 | 8 | 6 | 10 | | | | 1 | | | 2 | | 5 | 3 | 16 | | 6 | 100 | 17 | 5 | 17 | 2 | | 13 | 4 | 8 | | 4 | 3 | 7 | 12 | 8 |
| Cibicides lobatulus | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | |
| C. cf. refulgens | | | | | | | | | | 2 | 6 | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. robertsonianus | 12 | | | | | | | | | | | 2 | 6 | 5 | | | 10 | | | | | | 3 | 3 | | | | | 2 | 16 | | 7 | 6 | 6 | 4 | | | | | 2 | | |
| Cibicidina rhodiensis | | | | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cornuspira planorbis | | | | | | 5 | | 11 | 5 | 1 | | | | | | | | 3 | | | 2 | | 2 | | | | | | | | | | | | | | | | | | | |
| Discorbis cf. columbiensis | | | | | | | | 8 | 10 | 21 | 5 | 2 | | | | | | | 9 | | 14 | 17 | 5 | | | | | | | | | | | | | | | | | | | |
| D. williamsoni | | | | | | | | 19 | 3 | 6 | 3 | .4 | | | | | | | | | 2 | 17 | 3 | | | | | | | | | | | | | | | | | | | |
| D. obtusa | | | | | | | | | | | 2 | 4 | | | | | | | 9 | | | | | | | | | | | | | | | | | | | | | | | |
| Elphidium advenum | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eponides pusillus | | | | | 33 | 5 | | 8 | 2 | .7 | | | 31 | 5 | | | 15 | 28 | 18 | | | | 7 | 11 | 16 | 9 | 19 | | 10 | .6 | | | 9 | 10 | 26 | 6 | | 4 | 9 | 2 | | 13 |
| E. tumidulus | | | | | | 5 | | | | | | | | | | | | | | | | | 2 | 8 | 5 | | | | 7 | 3 | 8 | 2 | 2 | | 4 | 2 | | 8 | | 5 | | 2 |
| E. umbonatus and variants | | 67 | | | | 9 | | | | | | 1 | 12 | 15 | | | 20 | 13 | | | | | 7 | 11 | 11 | 3 | 16 | | 3 | 2 | 8 | 7 | 2 | 15 | 11 | 12 | 4 | 22 | 19 | 4 | 3 | 14 |
| Gyroidina orbicularis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 5 | .6 | | 2 | | | | | | | | | | |
| Eggerella bradyi | | | | | | | | | | | | .8 | | 5 | | | 5 | | | | | | | 3 | 3 | | 3 | | 2 | | | | 4 | | 2 | 2 | | | | | 2 | 3 |
| Laticarinina pauperata | | | | | | | | | | | | .4 | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | |
| Miliolids | | | | 17 | | | | 8 | | | 4 | 8 | | | 50 | | | | 9 | | 7 | | | | | | | | | | | | | | | | | | | | | |
| Nonion barleeanum | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| N. formosum | | | | | | | | | | | | 3 | 12 | 5 | | | 5 | | | | | | 2 | | 5 | | | | 3 | | | | | 3 | | | | | 2 | | .6 | |
| N. germanicum | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .6 | |
| N. pompilioides | | 11 | | | | | | | | | | 2 | | | | | | 3 | | | | | | | | 6 | 8 | | 3 | | | | | | 4 | | | 8 | 2 | | .6 | |
| Nonionella sp. | | | | | | | | 8 | | | | 2 | | | | | | | | | | | | | | 22 | | | | | | | | | | | | | | | | |
| N. sloanii | | | | | | | | | | | | 1 | 3 | | | | | | | | | | | | | 16 | | | | | | | | | | | | | | | | |
| Nummoloculina irregularis | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Patellina corrugata | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | | 11 | | | | | | | | | 1 | .8 | | 5 | 50 | | 5 | 3 | | | | | 5 | 8 | 8 | 6 | 6 | | 10 | | | | 6 | 6 | 4 | 6 | 7 | 8 | 3 | 7 | .6 | |
| Epistominella exigua | 25 | | | | | | 33 | 3 | | .7 | | 2 | 6 | 10 | | | 5 | 14 | | | | | 10 | 14 | 11 | 3 | 16 | | 18 | 10 | 25 | 14 | 15 | 19 | 12 | 17 | 19 | 4 | 25 | 40 | 20 | 39 |
| E. umbonifera | | | | | | | | | | | | .8 | 6 | 10 | | | 10 | 3 | | | | | 7 | | | 3 | 3 | | 7 | 27 | 21 | 26 | 24 | 3 | 2 | 6 | 60 | 2 | 21 | 5 | 5 | 3 |
| Pullenia bulloides | | | | | | 5 | | | | | 2 | .4 | 6 | 25 | | | | 10 | | | | | 3 | 17 | 11 | | 13 | | 2 | 2 | | | 6 | 6 | 9 | 12 | 7 | 8 | 8 | 11 | 18 | 16 |
| P. quinqueloba | 25 | | | 17 | | 5 | | | | | | | | | | | | | | | 2 | | 5 | 6 | 8 | 3 | 3 | | 7 | | | | | | 4 | 2 | | 14 | 8 | 7 | 5 | |
| P. cf. riveroi | | | | | | | | | | | | .8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P. sp. | | | | | | | | | | | | | | 5 | | | 5 | 10 | | | | | 3 | 3 | | 3 | | | 2 | .6 | 8 | 5 | 11 | 3 | | | | | | 2 | 1 | |
| Pyrgo murrhina | | | | | | | | | | | | 4 | 6 | | | | 15 | | | | | | | | | 3 | 6 | | 2 | 2 | 4 | 7 | 6 | 3 | 2 | | 4 | | | | 7 | |
| P. oblonga | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | |
| Quinqueloculina venusta | | | | | | | | | | | | .8 | | | | | | | | | | | | | | 3 | | | | | | | | | | 2 | | | | | | |
| Q cf weaveri | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Robulus | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | |
| "Rotalia" beccarii variant | | | | | | 9 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| "R" praegeri | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| "R." translucens | | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sigmoilina schlumbergeri | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .6 | |
| S tenuis | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .6 | | | | | | | | | | | | 2 |
| Spiroloculina sp. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Textularia australis | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Triloculina tricarinata | | | | | | | | | | | | .8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Uvigerina hollicki | | | | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Valvulineria araucana | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| V. humilis | | | 100 | | | | 67 | | 5 | | | | | | | | 5 | | 1 | | 5 | 17 | 2 | 14 | 5 | 6 | | | | 44 | 8 | 26 | 4 | 9 | 7 | 23 | | 10 | | 2 | | |
| Virgulina complanata | | | | | | 5 | | | | | | .4 | 6 | | | | | 3 | | | | | | | | | | | | .6 | | 2 | 2 | 3 | 4 | 2 | | 6 | | 2 | .6 | |
| | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | .6 | | | | | | | | | | | | |

the following benthonic species which are adapted to shallow water:

*Amphistegina lessonii*
*Angulogerina selseyensis*

*Bolivina globulosa*
*B. paula*
*B. pseudoplicata*
*B. pulchella*
*B. subaenariensis*
*B. tortuosa*

*Cassidulinoides mexicana*
*Cibicides* cf. *refulgens*
*Cornuspira planorbis*

*Discorbis* cf. *columbiensis*

*Nonionella sloanii*

*Virgulina mexicana*
*V. tessellata*

The following benthonic species probably are shoaler-water types:

*Bolivina* cf. *minuta*
*Discorbis williamsoni*
*Ophthalmidium inconstans*
*Rotamorphina laevigata*

*Globorotalia tumida* extends to 60 cm. *Globigerina hexagona* only occurs below 180 cm.

**Core 252.** The top fauna is not the same as the fauna in the surface sample from the same position, mainly in the lower frequencies of *Globorotalia tumida* and *Pulleniatina obliguiloculata*. There are numerous layers in this core which show evidence of intense solution, as evidenced by the very low populations in many samples. In addition, there are at least three rather thick layers containing a displaced fauna. Moreover, approximately 4 meters of core are missing in the material furnished the writers, between approximately 6 and 10 meters in the core. These facts greatly reduce the value of this core for any chronologic study and none is attempted.

TABLE 20. Occurrences of Foraminifera in selected samples from Core 254 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 254 DEPTH-4,337 M. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 2 | 3 | 6 | 9 | 10 | 13 | 15 | 16 |
| CM. FROM TOP OF CORE | 0.5-1 | 9.5-10 | 19.5-20 | 49.5-50 | 79.5-80 | 89.5-90 | 119.5-120 | 139.5-140 | 149.5-150 |
| PLANKTONIC POPULATION | 11,200 | 4,050 | 300 | 1,450 | 1,150 | 150 | 850 | 50,000 | 100 |
| Globigerina bulloides | .3 | .4 | 1 | .6 | | .6 | | .8 | |
| G. digitata | | .4 | 1 | .6 | | | | | |
| G. eggeri | 7 | 25 | 18 | | 36 | 3 | 69 | 2 | 11 |
| G. hexagona | | .4 | | 1 | .7 | | | 1 | |
| G. inflata | .3 | | | | | | .5 | | |
| G. pachyderma | | | .4 | | | | | | |
| Globigerinella aequilateralis | 1 | .8 | | .6 | | 1 | .5 | .5 | |
| Globigerinita glutinata | 4 | | .4 | .6 | .7 | 6 | | 11 | 1 |
| Globigerinoides conglobata | | .8 | 2 | 6 | 1 | 4 | 1 | .8 | 3 |
| G. rubra | 32 | 17 | 18 | 9 | | 28 | 3 | 39 | 31 |
| G. sacculifera | 45 | 41 | 30 | 23 | 14 | 33 | 3 | 29 | 19 |
| Globorotalia hirsuta | | .4 | | .6 | | | | | |
| G. menardii | .6 | | | | | | | | |
| G. menardii–tumida group | .3 | | 3 | 26 | 6 | 10 | 6 | 12 | 26 |
| G. punctulata | | .8 | 2 | 2 | | 1 | | .8 | |
| G. truncatulinoides | 3 | 11 | 4 | 3 | 5 | 8 | 16 | | 5 |
| G. tumida | 2 | | | | | | | | |
| Orbulina universa | 2 | | 2 | 3 | .7 | .6 | | R | |
| Pulleniatina obliquiloculata | 3 | 2 | 14 | 25 | 34 | 5 | 1 | 2 | 1 |
| [Sphaeroidina bulloides] | .3 | | | | | | 1 | | 1 |
| Sphaeroidinella dehiscens | | | | | 2 | | | | 2 |
| BENTHONIC POPULATION | 25 | 40 | 40 | 60 | 45 | 15 | 100 | 100 | 20 |
| Cassidulina subglobosa | | | | | | | 1 | 2 | 5 |
| Chilostomella oolina | | | | | | | 1 | | |
| Cibicides robertsonianus | 4 | | | 2 | 2 | | | | 5 |
| Eponides tumidulus | | 3 | | | 2 | | | | |
| E. umbonatus and variants | 17 | 6 | | 10 | 9 | | 1 | 4 | |
| Gyroidina soldanii variant | | | | 2 | | | 1 | | |
| Eggerella bradyi | 4 | 6 | 3 | 3 | 2 | | 1 | | 8 |
| Nonion formosum | | 8 | 3 | | | | | | |
| N. pompilioides | | 3 | | 2 | 5 | | | | 5 |
| Planulina wuellerstorfi | 4 | 11 | 11 | 3 | | | 6 | 2 | 5 |
| Epistominella exigua | 9 | 8 | 3 | 26 | 23 | 13 | 16 | 1 | |
| E. umbonifera | 30 | 33 | 81 | 44 | 32 | 80 | 67 | 13 | 54 |
| Pullenia bulloides | 13 | 3 | | 5 | 2 | | 3 | | 8 |
| P. quinqueloba | | 8 | | 2 | 11 | | 1 | | |
| P. sp | 4 | 6 | | | 2 | 7 | | | 5 |
| Pyrgo murrhina | 4 | 6 | | | 5 | | | 1 | 5 |
| Quinqueloculina venusta | | | | | | | | 1 | |
| Siphotextularia rolshauseni | 4 | | | | 5 | | | 1 | |
| Textularia australis | | | | 2 | | | 2 | 3 | |
| Virgulina bradyi | | | | | | | | 72 | |

The following shoaler-water benthonic species occur in the displaced sections:

*Amphistegina lessonii*
*Angulogerina selseyensis*
*Bolivina globulosa*
*B. paula*
*B. pseudoplicata*
*B. pulchella*
*B. subaenariensis*
*B. tortuosa*
*Bulimina exilis*
*B. marginata*
*B. mexicana*
*Cassidulina curvata*
*C. norcrossi australis*
*Cibicides* cf. *refulgens*

TABLE 21. Occurrences of Foraminifera in selected samples from Core 255 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 255 DEPTH-4,490 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 7 | 9 | 14 | 15 | 20 | 24 | 25 | 26 | 27 | 42 | 49 | 50 | 52 | 55 | 58 | 63 | 66 | 71 | 73 | 81 | 82 | 91 | 92 | 113 | 124 | 126 | 134 |
| CM. FROM TOP OF CORE | 1-1.5 | 39.5-40 | 59.5-60 | 79.5-80 | 129.5-130 | 139.5-140 | 189.5 190 | 229.5-230 | 239.5-240 | 249.5-250 | 259.5 260 | 409.5-410 | 483.5 484 | 489.5 490 | 509.5-510 | 539.5-540 | 569.5-570 | 619.5-620 | 649.5-650 | 699.5-700 | 719.5-720 | 799.5 800 | 809.5-810 | 899.5-900 | 909.5-910 | 1119.5 1120 | 1229.5 1230 | 1249.5-1250 | 1329.5-1330 |
| PLANKTONIC POPULATION | 15 400 | 11 200 | 1 150 | 165 | 1 500 | 2 400 | 95 | 7 | 5 | 500 | 1 300 | 150 | | 700 | 1 350 | 29 200 | 2 150 | | 17 | 50 | 6 200 | 165 | 23 450 | 320 | 3 300 | | | 3 550 | 105 |
| Candeina nitida | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Globigerina bulloides | .4 | | | | | .3 | | | | | .3 | 3 | | | .4 | 1 | 2 | | | | 2 | .6 | .3 | .8 | 2 | | | 1 | |
| G. digitata | | | .3 | | | | | | | .4 | | | | .6 | | | | | | 2 | .5 | | | | | | | | |
| G. eggeri | 10 | 7 | 24 | 69 | 38 | 61 | 84 | | | 33 | 32 | 54 | A | 32 | 15 | 4 | 18 | | 35 | 6 | 21 | | | 2 | 5 | | P | 24 | 59 |
| G. hexagona | .4 | 1 | | | | | | | | | | | | | .4 | 3 | | | | | | | 2 | | | | | .5 | |
| G. inflata | | | | 2 | 1 | .7 | | | | | | | | .6 | .4 | | 17 | | | 4 | | 1 | | 32 | 1 | | P | | |
| G. pachyderma | | | | .6 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Globigerinella aequilateralis | 3 | 5 | 1 | | | | | | | | | .7 | | 1 | .4 | 6 | 3 | | | 2 | | | 2 | .8 | .5 | | | 1 | |
| Globigerinita glutinata | | 4 | | | | | | | 20 | | | | | 1 | 4 | 1 | | | | | .5 | | 3 | | 8 | | | | |
| Globigerinoides conglobata | .8 | 1 | 1 | 2 | 4 | 2 | | | | 6 | 9 | | | 1 | 4 | 6 | 9 | | | 2 | 2 | 2 | 4 | 2 | 5 | | | 2 | 1 |
| G. rubra | 14 | 15 | 8 | | 2 | .7 | | 29 | | 2 | 3 | 1 | R | 2 | 13 | 32 | 8 | | | 4 | 31 | .6 | 36 | 5 | 24 | | | 21 | |
| G. sacculifera | 55 | 46 | 54 | 15 | 27 | 24 | 2 | 43 | 60 | 14 | 27 | 10 | R | 8 | 24 | 34 | 23 | | | 2 | 13 | 1 | 26 | 9 | 23 | | | 19 | 2 |
| Globorotalia hirsuta | | | | | | | | | | | | | | | | | | | 6 | | | | .5 | | | | | .5 | |
| G. menardii | 3 | — | — | — | — | — | — | — | — | — | → | | | | | 9 | | | | | | | | | | | | | |
| G. menardii-tumida group | | 13 | 2 | | 19 | | | 14 | 20 | .4 | | .7 | A | 36 | 42 | | .4 | | 18 | 10 | 23 | 54 | 9 | 14 | 11 | | P | 21 | 35 |
| G. punctulata | .8 | R | 5 | 6 | 2 | 3 | 6 | 14 | | 1 | 1 | 8 | R | | 2 | 1 | 1 | | 18 | 10 | 2 | 2 | | 3 | .5 | | | | |
| G. truncatulinoides | 2 | 2 | 4 | 6 | 4 | 8 | 5 | | | 9 | 5 | 2 | R | 3 | 3 | .2 | 8 | | 18 | 21 | 4 | 3 | 7 | .4 | 16 | | P | | |
| G. tumida | 5 | — | — | — | — | - - | - - | - - | - - | → | | | | | | | | | | | | | | | | | | | |
| Orbulina universa | 1 | .6 | .3 | | .5 | | | | | | .3 | | | 1 | | .2 | 1 | | | | .5 | 6 | .3 | .4 | | | | 1 | |
| Pulleniatina obliquiloculata | 3 | 4 | .7 | | 3 | | | | | 33 | 25 | 19 | R | 13 | 6 | 2 | 9 | | 6 | 6 | .5 | 32 | 9 | 27 | 8 | | | 7 | 4 |
| [Sphaeroidina bulloides] | | | | .6 | .5 | .3 | 2 | | | .8 | | 1 | | | | | .4 | | | | .5 | .6 | | .4 | | | P | | |
| Sphaeroidinella dehiscens | .4 | 2 | | | | | | | | | | | | | | .2 | .4 | | | | | 3 | | | | | | 1 | |
| BENTHONIC POPULATION | 100 | 50 | 30 | 5 | 20 | 45 | 15 | 1 | 3 | 20 | 20 | 16 | 20 | 20 | 20 | 140 | 35 | 133 | 12 | 2 | 70 | 25 | 40 | 8 | 20 | 44 | | 35 | 18 |
| Cassidulina subglobosa | 5 | 2 | 6 | | 11 | 5 | 12 | | | | 18 | 6 | 11 | 16 | 5 | .7 | 9 | | | | 8 | 4 | 3 | 13 | 21 | | | 4 | 6 |
| Cibicides robertsonianus | 3 | 6 | | | | 2 | | | | | | 6 | | | 5 | 1 | 6 | | | | | | 3 | | | | | 8 | |
| C. sp. | 1 | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | |
| Eponides tumidulus | | | | | | | | | | | | 6 | | | | | 3 | | | | | | | | | | | | |
| E. umbonatus and variants | 4 | 4 | 13 | 20 | 11 | 19 | 6 | | | 5 | 5 | 6 | 6 | 16 | | .7 | 3 | 4 | | | 11 | 15 | 3 | | 11 | 7 | | 16 | 6 |
| Gyroidina lamarckiana | | | | | | | | | | | | | | 6 | | .7 | | .8 | | | | | 3 | | | | | 4 | |
| G. soldanii variant | | | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | |
| Eggerella bradyi | 1 | | | 60 | | 5 | | | 33 | 28 | | 6 | 6 | | 10 | .7 | 6 | | | | | | | | 5 | | | 8 | 6 |
| Miliolids | | | | | | | | | | | | | | | | | | | | | 4 | | | | | | | 8 | |
| Nonion formosum | | | | | | | | | | 5 | 10 | 12 | | | | .7 | | 2 | 17 | | 3 | | | | | | | | |
| N. pompilioides | 1 | | 10 | | | 7 | | | | 10 | | | 6 | 16 | | .7 | 3 | 2 | | | | | | 13 | 5 | 7 | | | 6 |
| Planulina wuellerstorfi | .1 | 23 | 6 | 20 | 5 | 5 | | | | 10 | 18 | 6 | 6 | 11 | 15 | 2 | 3 | .8 | | | 4 | 12 | 3 | | 11 | | | 8 | 6 |
| Plectina apicularis | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Epistominella exigua | 1 | 2 | 3 | | 26 | | 19 | | .33 | | 10 | 19 | 16 | 16 | 15 | 24 | 15 | 8 | | 50 | 13 | 42 | 26 | | 5 | | | 4 | 11 |
| E. umbonifera | 63 | 50 | 13 | | 16 | 53 | 44 | 100 | 33 | 33 | 14 | 6 | 22 | 6 | 50 | 58 | 15 | 78 | 42 | 50 | 33 | 12 | 26 | 50 | 11 | 73 | P | 16 | 6 |
| Pullenia bulloides | 6 | 6 | 19 | | 5 | 2 | 6 | | | 10 | 10 | 12 | 16 | 6 | | 5 | 24 | | 8 | | 7 | 15 | 16 | | 11 | 13 | P | 8 | 28 |
| P. quinqueloba | | 2 | 26 | | 16 | 7 | | | | | 5 | 6 | 11 | | | 4 | 6 | 4 | 25 | | 7 | | 3 | 13 | 16 | | P | 12 | 1 |
| P. sp. | | | 3 | | 5 | | 12 | | | | 5 | 6 | | 6 | | | 3 | | | | | | | | | | | 4 | 6 |
| Pyrgo murrhina | 2 | 2 | | | | | | | | | 5 | | | | | | | | | | 4 | | 3 | | | | | | |
| P. oblonga | | | | | | | | | | | | | | | | | | | | | 1 | | | 13 | | | | | |
| Quinqueloculina venusta | | | | | | | | | | | | | | | | .7 | | | | | | | | | 5 | | | | |
| Q. cf. weaveri | | | | | | | | | | | | | | | | .7 | | | | | | | | | | | | | |
| Robulus | | | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | |
| Siphotextularia rolshauseni | | | | | | | | | | | | | | | | .7 | 3 | .8 | | | 3 | | 5 | | 1 | | P | | 11 |
| Textularia australis | 1 | 2 | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | |
| Valvulineria humilis | | | | | 5 | | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina complanata | | | | | | 2 | | | | | | | | | | | | | 8 | | | | | | | | | | |

*Cibicidina rhodiensis*
*Cornuspira planorbis*
*Discorbis* cf. *columbiensis*
*D. obtusa*
*Elphidium advenum*
*Nonionella sloanii*
*Pullenia* cf. *riveroi*
*»Rotalia» beccarii*
*»R.» translucens*
*Valvulineria araucana*
*Virgulina mexicana*
*V. tessellata*

Displaced faunas occur at 50 to 230 cm., at 399.5 to 580 cms., and at 1,116—1,116.5 cm. In addition, there is one displaced specimen at 2.5—3 cm.

*Globorotalia tumida* extends to 10 cm.

**Core 254.** The faunas in this short core suggest two shifts from tropical to semi mid-latitude conditions. *Globorotalia tumida* occurs only in the top sample, and *Globigerina hexagona* occurs in a few samples below 10 cm.

**Core 255.** This core shows three mid-latitude faunas separated by low-latitude assemblages. There are numerous zones of intense solution. *Globorotalia tumida* extends to 250

TABLE 22. Occurrences of Foraminifera in selected samples from Core 257 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 257 DEPTH - 4,470 M.

| SAMPLE | 1 | 5 | 7 | 8 | 9 | 10 | 13 | 14 | 17 | 20 | 21 | 22 | 23 | 25 | 27 | 32 | 43 | 44 | 45 | 48 | 50 | 56 | 58 | 62 | 70 | 75 | 78 | 83 | 86 | 87 | 88 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 2-2.5 | 39.5-40 | 59.5-60 | 69.5-70 | 79.5-80 | 90-90.5 | 119.5-120 | 129.5-130 | 159.5-160 | 189.5-190 | 200-200.5 | 209.5-210 | 219.5-220 | 239.5-240 | 259.5-260 | 309.5-310 | 419.5-420 | 429.5-430 | 439.5-440 | 469.5-470 | 489.5-490 | 553-553.5 | 569.5-570 | 611.5-612 | 699.5-700 | 749.5-750 | 779.5-780 | 819.5-820 | 847-847.5 | 857.5-858 | 867.5-868 |
| PLANKTONIC POPULATION | 3,900 | 8,400 | 1,400 | 28 | 26 | 175 | 100 | 120 | 990 | 55 | 116 | 3 | 84 | 250 | 47 | 435 | 79 | 18 | 1 | 21 | 11 | 13 | 13 | 22 | 20 | 28 | 30 | 45 | 75 | 17 | 16 |
| Candeina nitida | .4 | .4 |  |  |  | 1 |  |  |  |  |  |  |  | .8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Globigerina bulloides | 2 | 1 | 4 | 18 | 8 | 2 |  | 3 | 7 |  | 8 |  |  | 3 | 6 | 1 |  |  |  | 5 |  |  |  | 9 | 5 | 14 | 3 | 2 | 11 |  |  |
| G. eggeri | 4 | 3 | 6 | 7 |  | 11 | 77 | 44 | 16 | 53 | 12 |  | 55 | 25 | 13 | 33 | 28 | 6 |  | 24 |  | 23 |  | 14 | 20 | 11 | 13 | 20 | 7 | 18 |  |
| G. inflata |  | .4 | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. pachyderma |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 |  | 3 |  |  |  | 6 |
| Globigerinella aequilateralis | 5 | 5 | 3 | 4 | 4 | 5 |  |  | .4 |  |  |  |  | .4 |  | .2 | 3 |  |  | 5 | 9 |  |  |  | 5 |  |  |  | 4 |  |  |
| Globigerinita glutinata | .8 | 4 | .6 | 43 | 8 | 8 | 2 |  | 5 |  | 4 |  | 2 | 4 | 6 | 3 | 3 | 17 |  |  | 9 |  |  |  | 5 | 7 | 10 |  | 7 |  |  |
| Globigerinoides conglobata | 1 | .4 | .6 |  |  | .6 |  | .8 | 1 | 2 | 3 |  | 2 | .4 |  | 1 | 3 | 6 |  |  |  |  |  | 5 |  |  |  |  |  |  |  |
| G. rubra | 31 | 32 | 24 | 14 | 35 | 34 |  | 8 | 41 | 6 | 41 |  | 20 | 40 | 57 | 25 | 22 | 50 |  | 29 | 45 | 38 | 46 | 32 | 30 | 50 | 45 | 29 | 45 | 35 | 56 |
| G sacculifera | 45 | 43 | 41 | 4 | 35 | 36 | 1 | 18 | 17 | 4 | 20 | 33 | 10 | 21 | 9 | 28 | 34 | 17 | 100 | 29 | 18 | 23 | 46 | 23 | 25 | .1 | 23 | 38 | .5 | 24 | 25 |
| Globorotalia menardii | 4 ⟶ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | ⟶ |  |  |  |
| G. menardii-tumida group |  | 3 | .6 | 4 |  | .6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 |  |  |  | 2 |  | 18 |  |
| G. punctulata |  | .4 | 3 |  |  |  | 17 | 25 | 6 | 35 | 10 | 67 | 8 | 2 |  | 4 | 9 |  |  |  |  | 8 | 8 |  |  |  |  | 2 | 1 |  | 6 |
| G scitula |  | .4 | .6 | 4 |  | .6 |  |  | .4 |  |  |  |  | .4 | 6 | .2 |  |  |  |  | 18 |  |  |  |  | 7 |  |  |  |  |  |
| G. truncatulinoides | .8 | 3 | 4 | 4 | 4 | .6 | 2 | .8 | 6 | 2 | 3 |  | 2 | 2 | 2 | 2 |  | 6 |  | 5 |  | 8 |  |  |  |  |  | 2 | 11 | 6 | 6 |
| G tumida | 3 ⟶ |  |  | ⟶ |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Orbulina universa | 2 | 2 |  |  | 4 |  |  |  |  |  |  |  |  | .4 |  | 1 |  |  |  | 5 |  |  |  | 9 |  |  | 3 |  |  |  |  |
| Pulleniatina obliquiloculata | 2 | 3 | 11 |  | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5 | 5 |  |  | 4 |  |  |  |
| [Sphaeroidina bulloides] |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  | .2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| BENTHONIC POPULATION | 46 | 79 | 29 | 1 | 3 | 2 | 10 | 11 | 13 | 13 | 4 | 4 | 18 | 17 | 1 | 15 | 0 | 9 | 6 | 7 | 28 | 2 | 8 | 5 | 16 | 22 | 12 | 9 | 70 | 8 | 10 |
| Bolivina pseudopunctata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B. subaenariensis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 22 |  | 28 | 29 | 50 | 25 | 20 | 12 | 18 | 33 | 44 | 23 | 62 | 10 |
| B. sps. |  |  |  |  |  |  |  |  |  |  |  | 75 |  |  |  |  |  | 11 | 17 |  | 43 |  |  | 20 | 12 | 28 | 8 |  | 9 |  | 10 |
| Bulimina aculeata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 7 |  |  | 50 | 25 |  |  |  | 8 | 11 | 0 |  | 20 |
| B. alazanensis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 20 |  |  |  |  |  |  |  |
| B exilis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 | 17 | 14 | 4 |  |  |  | 6 |  | 8 |  | 1 |  |  |
| B marginata variant |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 |  |  |  |  | 12 | 40 | 37 | 14 | 25 | 22 | 13 |  |  |
| B. translucens |  |  | 3 |  | 33 |  |  |  |  | 15 |  |  | 6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Cassidulina carinata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 |  |  | 11 |  |  |  |  | 9 | 17 |  |  |  |  |
| C. norcrossi australis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 7 |  |  |
| C. subglobosa | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 17 | 14 |  |  |  |  |  |  |  |  |  |  |  |
| Cibicides lobatulus |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 14 |  |  |  |  |  |  |  |  |  |  |  |
| C. cf. refulgens |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 12 | 10 |
| C. robertsonianus |  | 3 | 10 |  |  |  |  |  | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Discorbis bertheloti |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 10 |
| Eponides pusillus |  | 1 | 3 |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| E. umbonatus and variants |  | 4 | 7 |  |  |  |  |  | 8 |  |  |  | 17 | 12 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Gyroidina lamarckiana | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. soldanii variant | 7 | 1 |  |  |  |  |  |  |  |  |  |  |  | 6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eggerella bradyi | 2 | 1 |  |  |  |  |  |  |  | 23 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Miliolids |  |  |  |  |  |  |  |  | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 11 |  |  |  |
| Nodosaria sps |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 17 |  |  |  |  |  |  |  |  |  |  |  |  |
| Nonion germanicum |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| N. pompilioides |  |  |  |  |  |  |  |  | 8 |  |  |  |  | 6 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nonionella atlantica |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 |  |  |  |  |  |  |
| N. sloanii |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 7 |  |  |  |  | 4 |  |  |  |  |  |
| Planulina wuellerstorfi | 20 | 4 | 7 |  |  | 50 |  | 18 |  | 8 |  |  | 11 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |
| Plectina apicularis | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Epistominella exigua | 2 | 11 | 17 |  | 33 |  | 30 | 45 |  |  | 100 |  | 33 | 24 |  | 53 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| E. umbonifera | 57 | 66 | 45 | 100 | 33 | 50 | 20 | 18 | 8 | 8 |  | 25 | 11 | 18 |  | 27 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Pullenia bulloides |  | 5 | 7 |  |  |  |  |  |  |  |  |  |  | 18 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| P. quinqueloba | 4 |  |  |  |  |  | 10 | 18 | 31 | 23 |  |  | 6 | 6 | 100 | 7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| P. sp. |  |  |  |  |  |  | 30 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Pyrgo oblonga |  |  |  |  |  |  |  |  | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| "Rotalia" beccarii variant |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 22 | 17 | 28 | 7 |  | 25 |  | 12 | 18 |  | 11 | 26 |  | 20 |
| Siphotextularia rolshauseni |  |  |  |  |  |  |  |  | 23 | 15 |  |  | 11 | 6 |  | 13 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Textularia australis | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Uvigerina sp. 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 12 |  | 6 | 9 |  |  | 10 |  | 20 |
| U. sp. 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 25 |  |
| Virgulina complanata |  |  |  |  |  |  |  |  |  | 8 |  |  | 6 | 6 |  |  |  |  |  |  |  |  |  |  | 6 |  |  |  |  |  |  |

cm., and *Globigerina hexagona* is present in the top of the core. The sample at 900 cm. contains a mixed planktonic fauna.

**Core 257.** There appear to be approximately five shifts from low-latitude to cooler-water faunas in the upper 430 cm. of this core. Most of the samples have low populations, having suffered rather intense solution, and their reliability is thus somewhat questionable. *Globorotalia tumida* extends to 70 cm.

From 429.5 cm. to the bottom of the core at 868 cm. there is a displaced fauna, based upon the following shoaler-water benthonic species which occur in these lower samples:

*Bolivina subaenariensis*
*Bulimina exilis*
*B. marginata*
*Cassidulina norcrossi australis*
*Cibicides* cf. *refulgens*
*Discorbis bertheloti*
*Nonionella sloanii*

TABLE 23. Occurrences of Foraminifera in selected samples from Core 258 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 258 | DEPTH-4,554 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE |1|5|9|10|11|15|27|31|36|41|42|44|45|49|50|53|55|56|57|58|59|60|61|62|63|64|67|83|86|87|90|92|93|102|
| CM. FROM TOP OF CORE |5.5-6|37.5-38|69.5-70|79.5-80|90.6-91|133-133.5|259.5-260|299.5-300|349.5-350|399.5-400|409.5-410|429.5-430|434-435.5|459.5-460|469.5-470|499.5-500|519.5-520|529.5-530|539.5-540|549.5-550|559.5-560|569.5-570|579.5-580|589.5-590|599.5-600|609.5-610|639.5-640|797-797.5|829.5-830|839.5-840|869.5-870|889.5-890|899.5-900|979.5-980|
| PLANKTONIC POPULATION |10,900|12,250|410|19|17|177|390|38|63|19|19|250|57|1,770|850|450|3,950|43|530|80|1,950|131|21|2,150|13|1,000|630|18|6|21|92|19|2|4|
| Candeina nitida |1|1|||||.3||||||||||||||||||||||||||||||
| Globigerina bulloides |3|5|2||1|1|5||6|5|5|3||5|2|4|6||||2|.8||3||1|.8|5||||26|50|25|
| G. digitata ||||||6||3|||||||||||||||||||||||||||
| G. eggeri |9|2|17|63|71|38|9|63|17|32|47|19|68|29|62|43|28|58|20|14|42|32|57|45|92|49|48|22|33|33|27|11||25|
| G. inflata ||||||2|2|||||5||1||1|.4|||1|||||||||||||||
| G. pachyderma |||||1||||||||||||||||||||||||||||||
| Globigerinella aequilateralis |2|2|2||3|1|.8|||||||||||.4||.8|1|||||||1|5|||1|||25|
| Globigerinita glutinata |.6|3|.5|||1|4|||||3|2|4||.4|3|2|1|1||||.4||1|||||||50||
| Globigerinoides conglobata |2|.5|.5|||.6|1|5|||5|.8|2||1|4|.4||.8||2|1||2|||1|5|||||||
| G. rubra |33|46|23|21|1|23|46|3|29|26|5|40|9|45|5|35|43|7|27|49|7|26||11||16|10|17||43|29|37|||
| G. sacculifera |38|30|27||9|25|25|13|36|16|10|16|3|8|16|7|12|12|44|21|23|21|5|19||14|17|17|33|14|24|5|||
| Globorotalia hirsuta |||||||||||||||||||||||||||||||1||||
| G. menardii |4 →|||||||||||||||||||||||||||||||||→|
| G. menardii–tumida group ||2|2||4||||||5|||||||||||||||||6|33|5||11||25|
| G. punctulata |.6|.8|2|5|3|1|.8||6||5|7|9|3|12|2|2|21|2|1|2|5|5|.4||.4|1||||2||||
| G. scitula ||1|||||2|||5||2|2|4||.4|1||.4|1||||.4|||||||2|11|||
| G. truncatulinoides |1|3|1|||5|2|11|2|16|5|4|5|1|3|3|3||3|7|7|5||4||6|3|22|||3||||
| G. tumida |2 →||||→|||||||||||||||||||||||||||||
| Orbulina universa |1|1|3||3|2|.3|3|3|||.8|||||||.8||||||||.8|||||||
| Pulleniatina obliquiloculata |2|1|20|10|4||||||||||||||||2|14|8|33|14|8|12|16|||5|10||||
| Sphaeroidinella dehiscens ||.3|||||||||||||||||||||||||||||||||
| BENTHONIC POPULATION |78|51|38|45|15|12|0|2|4|6|7|6|37|24|46|18|38|144|39|15|34|13|30|25|50|38|47|6|4|23|33|10|6|2|
| Bolivina subaenariensis ||||||||||17||||||||||13|||||||||25|39|21|10|||
| B. sps. |||||||||||14|||||||||7||||||||33||22|18|10|17||
| Bulimina aculeata ||||||||||||||||||||7||||||||33|25|4|9||||
| B. exilis ||||||||||||||||||||||||||||||||10|17||
| B. marginata variant |||||||||||29||||||||||3||||||||||9||50||
| B. translucens ||||||||||||||||||||7|3||||||||||||||
| Cassidulina carinata ||||||||||||||||||||33||||||||||17|15|||50|
| C. crassa ||||||||||||||||||||||||||||||4|||||
| C. subglobosa ||2||||||||||||||||||||||4||3|6|||4|||||
| Cibicides robertsonianus |1|4|||||||||||||||3|||||8|||||||||||||
| C. sp. |||||||||||||||2|||||||||||||||||||||
| Eponides pusillus |||||7||||||||||||||3|||||||||||||||||
| E. umbonatus and variants |4|4|5|2|7||||25|||17|3|8|2||8|3|||6|||8|18|24|6||||3||||
| Globobulimina affinis |||||||||25||||||||||||7||||||||||||20|||
| Gyroidina lamarckiana |3||||||||||||||2|||||||||||||||||||||
| G. soldanii variant ||2||2||||||||||||||.7|||||||||||||||||
| Eggerella bradyi |3|||2|7|8||||||17||4|7||||10||6||3|4|2||2|||||||||
| Nonion formosum |||||||||||||||4|||||||||4|||||||||||
| N. pompilioides |||||||||||||||4||3||||6||3||2||6|||||||||
| Nonionella atlantica ||||||||||33||||||||||||||||||||||10|||
| Nummoloculina irregularis ||||||||||17|||||||||||||||||||||||||
| Osangularia cultur ||||||||||||||||||||7||||||||||||||
| Planulina wuellerstorfi |11|12|10|4|7|8|||||||3|4||6|8|1|13||6|15|7||2||2|||||||||
| Plectina apicularis |3|4|3|||||||||||||||||||||||||||||||
| Epistominella exigua ||4|8|25||25|||25||14|50|46|46|22||10|19|3|13|9|8|33|40|38|26|28|||||||
| E. umbonifera |62|57|60|62|53|25||50|||||35|21|33|78|59|73|66||41|69|43|24|36|31|13|17|||||||
| Pullenia bulloides |5|8|10|2|||||||||||7||3||||6|||4||3|2|||||||
| P. quinqueloba |4||3|||25|||||||11|8|11|11|5|1|3||3||7|4|2|3|6|||||||
| Pyrgo murrhina ||||||8|||25|17||||8|2||||3||6|||8||5|11|||||||
| P. oblonga ||||||||||||||||||||||3||||||4|||||||
| Quinqueloculina venusta |||||||||||||||2|||||||||||3|2|||||||
| Q. cf. weaveri |||||12||||||||||||||||||||||||||||||
| Robulus |||||||||||||||||3||||||||||2|||||||
| "Rotalia" beccarii variant ||||||||||||||||||||||||||||||25|4||10||50|
| Siphotextularia rolshauseni |1|||||||||||||||||||||||||||||||||
| Textularia australis |3|2||||||||||||||||||||||||||||||||
| Triloculina tricarinata ||||||||||||||||||||7||||||||||||||
| Uvigerina sp. 1 ||||||||||17|29||||||||||||||||||17|25||21||17||
| U. sp. 2 ||||||||||||||||||||||||||||||4|3|20|||
| Virgulina bradyi |||||||||||||||||||||||||||9|||||||
| V. complanata ||||||||50|||14|17|||2|6||.7||||||||||||||||
| Pullenia sp. |||||7|||||||||3|||||||3|||||3|||||||||

*»Rotalia» beccarii*
*Uvigerina* sp. 1
*U.* sp. 2

**Core 258.** The top samples contain a low-atitude fauna and a normally high population. elow about 80 cm. there is evidence of intenive solution in most of the samples and thus the populations are variable and unreliable. The upper low-latitude fauna appears to extend to approximately 120 cm., the next lower fauna seems to have mid-latitude affinities to about 520 cm., and below this the fauna appears low-latitude in aspect. *Globorotalia tumida* extends to 91 cm.

Three layers have been recognized with

faunas displaced from shallow water. At 399.5—410 cm. the following shallow-water benthonic species are present:

*Bolivina subaenariensis*
*Bulimina marginata*
*Uvigerina* sp. 1

At 549.5—560 cm. the following shallow-water benthonic species occur:

*Bolivina subaenariensis*
*Bulimina marginata*

The following shallow-water benthonic species occur from 797 cm. to the bottom of the core:

*Bolivina subaenariensis*
*Bulimina exilis*
*B. marginata*
*»Rotalia» beccarii*
*Uvigerina* sp. 1
*U.* sp. 2

**Core 261.** This short core, only 40 cm. long, seems to have a low-latitude fauna throughout. The fauna in the top sample is somewhat different fromt he surface sample collected from the same station. *Globorotalia tumida* is 38% of the surface sample and is not recorded in the core. *Globigerina eggeri* is 29% of the surface sample and does not occur in the core. The material collected at this station has had extensive solution, and this may account for the faunal irregularities.

**Core 262.** This core has had extensive solution of calcium carbonate and as a result most of the 130 samples examined either contain no Foraminifera or only a few fragments. Only three samples contained enough specimens for analysis and these faunas have been modified by solution. Sample 4 at 29.5—30 cm. contains what appears to be a mid-latitude fauna not characteristic for the latitude at which it was collected. Sample 6 at 49.5—50 cm. has a low-latitude assemblage, and the fauna in sample 130 at 1,279.5—1,280 cm. has a mid-latitude composition. *Globorotalia tumida* is not present. There is a displaced fauna a 1,279.5—1,280 cm., indicated by the presenc of the following benthonic species:

*Bolivina subaenariensis*
*Bulimina exilis*
*B. marginata*
*Uvigerina* sp. 1

TABLE 24. Occurrences of Foraminifera in selecte samples from Cores 261, 262 and 263 in percent of tota population. Planktonic and benthonic populations computed separately.

| CORE | 261 | | 262 | | | 263 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DEPTH-M. | 5,128 | | 5,480 | | | 5,320 | | | | |
| SAMPLE | 1 | 5 | 4 | 6 | 130 | 1 | 5 | 97 | 98 | 110 |
| CM. FROM TOP OF CORE | 0.5-1 | 39.5-40 | 29.5-30 | 49.5-50 | 1279.5-1280 | 1-1.5 | 39.5-40 | 939.5-940 | 950-950.5 | 1069.5-1070 |
| PLANKTONIC POPULATION | 100 | 500 | 120 | 250 | 90 | 135 | 125 | | 1,150 | 10 |
| Globigerina bulloides | 2 | 1 | | .8 | 13 | | | | .7 | 20 |
| G. digitata | 1 | | | | | | | | | |
| G. eggeri | | | 36 | 18 | 3 | 31 | 26 | A | 39 | 70 |
| G. hexagona | 16 | 2 | | | 1 | | | | | |
| G quinqueloba | | | | | | | | | .7 | |
| Globigerinella aequilateralis | 2 | .8 | | | 1 | | 2 | | | |
| Globigerinita glutinata | | | | 27 | 13 | | | | | |
| Globigerinoides conglobata | 5 | 7 | 5 | 2 | | 4 | 11 | R | 11 | |
| G. rubra | 21 | 10 | 3 | 13 | 47 | 4 | 10 | R | 5 | 10 |
| G. sacculifera | 23 | 9 | 4 | 9 | 5 | 11 | 22 | | 6 | |
| Globorotalia hirsuta | | | | .4 | | | | | | |
| G menardii | | | | | | | 2 | → | | |
| G menardii-tumida group | 11 | 24 | | 14 | 2 | | | A | 11 | |
| G. punctulata | 2 | 7 | .8 | | | 2 | 5 | R | 2 | |
| G scitula | | | | | 13 | | | | | |
| G truncatulinoides | 4 | 2 | 34 | 3 | 2 | .7 | 3 | | 5 | |
| G. tumida | | | | | | 28 | 10 | | | |
| Orbulina universa | 1 | 2 | .8 | | | | .8 | | 1 | |
| Pulleniatina obliquiloculata | 8 | 35 | 15 | 14 | | 13 | 7 | C | 14 | |
| [Sphaeroidina bulloides] | | | .8 | | | | | | | |
| Sphaeroidinella dehiscens | 2 | .4 | 2 | 1 | | 7 | .8 | C | 3 | |
| BENTHONIC POPULATION | 5 | 18 | 80 | 55 | 45 | 95 | 80 | | 70 | 0 |
| Bolivina pseudopunctata | | | | | 2 | | | | | |
| B subaenariensis | | | | | 7 | | | | | |
| B sps | | | | | 2 | | | | | |
| Bulimina exilis | | | | | 5 | | | | | |
| B. marginata variant | | | | | 14 | | | | | |
| Cassidulina carinata | | | | | 16 | | | | | |
| C. subglobosa | | 6 | 1 | | | | | | | |
| Cibicides sp | | | | | 2 | | | | | |
| Eponides tumidulus | | | | | | | 1 | | | |
| E. umbonatus and variants | | 6 | | 2 | 9 | 4 | 1 | | 3 | |
| Gyroidina soldanii variant | | 6 | 1 | | | | 1 | | | |
| Nonion pompilioides | | | | 2 | | | | | 1 | |
| Nonionella atlantica | | | | | 9 | | | | | |
| Planulina wuellerstorfi | | 6 | 4 | | | 4 | 1 | | 4 | |
| Epistominella exigua | | 28 | | 2 | 9 | 2 | 1 | | 4 | |
| E. umbonifera | 80 | 50 | 86 | 82 | 2 | 81 | 90 | A | 81 | |
| Pullenia bulloides | | | 1 | 9 | | 2 | 1 | | 1 | |
| P quinqueloba | | | 4 | 4 | 2 | 2 | 1 | | 3 | |
| P sp | | | | | 2 | 3 | 1 | | 1 | |
| Pyrgo murrhina | | | | | 5 | 1 | | | | |
| Uvigerina sp 1 | | | | | 9 | | | | | |
| Virgulina complanata | | | | | 2 | | | | | |

**Core 263.** This core has had intensiv solution, and only five sample have sufficien specimens for analysis. The upper 40 cm contains a typical low-latitude fauna. *Globoro talia tumida* occurs at high frequency in thi layer and is not recorded lower in the core Samples 97 and 98 at 939.5 to 950.5 cm. als

TABLE 25. Occurrences of Foraminifera in selected samples from Core 267 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 267 | DEPTH - 2,105 M. | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 10 | 15 | 21 | 24 | 30 | 31 | 36 | 38 | 44 | 50 | 55 | 59 | 63 | 68 | 77 | 82 | 85 | 88 | 92 | 97 | 102 | 106 | 112 | 116 | 120 |
| CM. FROM TOP OF CORE | 0-1 | 39.5-40 | 89.5-90 | 139.5-140 | 189.5-190 | 219.5-220 | 279.5-280 | 289.5-290 | 339.5-340 | 359.5-360 | 419.5-420 | 479.5-480 | 529.5-530 | 569.5-570 | 609.5-610 | 659.5-660 | 749.5-750 | 799.5-800 | 829.5-830 | 859.5-860 | 939.5-940 | 949.5-950 | 999.5-1000 | 1039.5-1040 | 1099.5-1100 | 1139.5-1140 | 1179.5-1180 |
| PLANKTONIC POPULATION | 35,100 | 26,400 | 13,900 | 14,900 | 39,200 | 58,100 | 11,500 | 13,500 | 21,700 | 19,800 | 8,000 | 11,000 | 18,800 | 13,100 | 16,200 | 9,100 | 12,500 | 26,800 | 17,200 | 17,900 | 17,000 | 33,200 | 5,400 | 16,300 | 9,900 | 7,800 | 21,500 |
| Candeina nitida | 3 | 1 | | | .3 | | | | | | | | | | | | | | | | | | | | | | |
| Globigerina altispira | | | | | | | | | | | | | | | 3 | 4 | 3 | 2 | 4 | 7 | 1 | 5 | | 1 | | | |
| G. bulloides | 8 | .7 | 3 | 4 | 4 | 1 | 2 | 4 | 4 | 3 | 8 | 3 | 5 | 6 | 2 | 4 | 1 | 2 | 1 | .7 | 1 | 1 | 3 | 3 | 4 | 1 | 4 |
| G. digitata | | | | .4 | .3 | | | .2 | | | | | .3 | | | | | | | | | | | | | | |
| G. eggeri | 2 | 6 | 6 | 9 | 8 | 20 | 19 | .7 | 2 | 19 | 6 | 15 | 6 | 7 | 6 | 3 | 1 | 2 | 6 | 2 | 3 | 7 | 6 | 4 | 11 | 13 | 16 |
| G. hexagona | | | | | 1 | .4 | 2 | 3 | .3 | | .8 | | 1 | 1 | | 1 | | .7 | | | | | | | 2 | | |
| G. inflata | | | | | | | | | | | | | | | | | | .2 | .4 | 2 | | 1 | 6 | | 1 | | |
| G. pachyderma | | | | | | .2 | | | | | | | | | | | | | .7 | .7 | 3 | 2 | | | | | |
| G. quinqueloba | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | |
| G. venezuelana | | | | | | | | | | | | | | | 1 | .7 | 1 | 1 | 2 | 3 | 1 | 2 | | | | | |
| Globigerinella aequilateralis | 7 | 3 | 2 | 3 | 2 | 3 | 2 | 5 | 3 | 5 | 6 | 2 | 6 | 5 | .8 | 6 | 4 | 2 | .7 | 2 | 2 | 2 | 1 | 3 | 1 | .4 | 1 |
| Globigerinita glutinata | 4 | 5 | 6 | 6 | 6 | 1 | 5 | 4 | 2 | 3 | 5 | 4 | 4 | 5 | 3 | | 6 | 3 | 7 | 7 | 3 | 1 | 1 | .8 | 2 | 2 | |
| Globigerinoides conglobata | | .7 | .5 | 1 | 2 | .2 | .6 | 2 | 1 | .3 | .8 | 2 | 2 | 2 | 1 | .7 | 1 | | .4 | | | .4 | .6 | | .6 | 3 | .6 |
| G. rubra | 56 | 49 | 50 | 43 | 48 | 52 | 45 | 50 | 48 | 43 | 46 | 49 | 61 | 52 | 55 | 60 | 63 | 65 | 65 | 61 | 67 | 55 | 61 | 65 | 52 | 52 | 54 |
| G. sacculifera | 7 | 20 | 12 | 9 | 13 | 13 | 9 | 16 | 19 | 11 | 9 | 13 | 6 | 12 | 15 | 9 | 5 | 12 | 7 | 7 | 9 | 10 | 16 | 14 | 23 | 19 | 14 |
| Globorotalia menardii | 1 — | | | | | | | | | | | | | | | | | | | | | | | | | | → |
| G. menardii-tumida group | .7 | 2 | 13 | 14 | 10 | 1 | 9 | 9 | 8 | 9 | 8 | 6 | 4 | 3 | 6 | 6 | 6 | .2 | | .4 | | .8 | 1 | 4 | | .4 | 1 |
| G. punctulata | R | | 2 | 3 | 2 | .7 | .6 | .7 | | .3 | .4 | | | | | | 3 | .2 | | .4 | | .2 | .6 | .4 | | | |
| G. scitula | .7 | 4 | 1 | 2 | 2 | .4 | 3 | 3 | 1 | 2 | 4 | 1 | .3 | 2 | 2 | 2 | .5 | 3 | 5 | 3 | 4 | 2 | 4 | 2 | 1 | 3 | 1 |
| G. truncatulinoides | R | 2 | 2 | .4 | 2 | 3 | 1 | .5 | 5 | 2 | 2 | 4 | 2 | 4 | 4 | 2 | | 2 | .7 | 2 | .4 | 5 | 2 | .8 | 1 | 4 | 3 |
| G. tumida | .4 | → | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. sp. 2 | | | R | | | | | | R | R | | | | | | | | | | | | R | | R | | R | R |
| Orbulina universa | 10 | 4 | | 2 | .3 | 2 | 1 | .2 | .6 | 1 | 4 | .3 | 1 | 5 | .4 | 2 | 5 | 2 | | 1 | .7 | 1 | | 1 | 3 | 1 | .6 |
| Pulleniatina obliquiloculata | | 2 | 1 | 2 | 1 | .7 | | 2 | 6 | .3 | .8 | | | .5 | .8 | | .5 | 1 | | .4 | 2 | 2 | 1 | 2 | .6 | | .3 |
| Sphaeroidinella dehiscens | | .2 | | | | | | | .3 | | | | | .5 | | | | .2 | | .4 | .4 | .2 | .6 | | | | .3 |
| BENTHONIC POPULATION | 170 | 45 | 65 | 30 | 50 | 50 | 30 | 25 | 55 | 40 | 20 | 30 | 25 | 30 | 25 | 15 | 25 | 20 | 20 | 30 | 15 | 45 | 20 | 90 | 45 | 25 | 30 |
| Amphistegina lessonii | | | 1 | | | | | | 2 | | | | | | | | | | | | | | | | | | 3 |
| Angulogerina selseyensis | | 2 | | 3 | | | | | | 2 | 4 | 3 | 7 | | | | | | | | 6 | | 10 | | 4 | | 7 |
| Bolivina globulosa | | | | | | | | | | | | | | | | | | | | | 6 | | | | | | |
| B. cf. minuta | 1 | 2 | 3 | 3 | 2 | | 3 | | | 2 | 4 | | | 17 | 4 | | | | | 4 | 6 | 7 | | | 2 | | |
| B. paula | 7 | | | | | 2 | | | | | | | | | | | | | | | | | 5 | 1 | | | |
| B. pulchella | | | | | | | | | 2 | | | | | | | | | | | | | | 10 | 1 | | | |
| B. pseudoplicata | 10 | | | | 2 | 2 | 3 | | 2 | | 4 | 3 | | | 4 | | 4 | | 9 | | 23 | 2 | | 2 | | | 3 |
| Bulimina aculeata | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | |
| B. alazanensis | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| B. mexicana | | | | | | | | | | | 4 | | | | | | | | | | | 2 | | | | | 3 |
| Cassidulina carinata | | | | | | | | | | | | | | 4 | | | | | | | | 5 | | | | | |
| C. crassa | | | | | 2 | 2 | 3 | | | 2 | | | | | | | | | | | | | | | | | |
| C. subglobosa | 7 | 16 | 1 | 6 | | | 3 | | 3 | 2 | 9 | | | | 4 | | | | | 4 | | | | 1 | 4 | | |
| Chilostomella oolina | | | | | | | | | | | | | | | | | 4 | | | | | | | | | | |
| Cibicides kullenbergi | 1 | 2 | 1 | | 13 | | 7 | 4 | | 2 | | | | | | | | | | | | | | 2 | | 4 | |
| C. cf. refulgens | | | | | | | | | | | | | | | | | 4 | | 5 | 4 | | 16 | 5 | | | | |
| C. robertsonianus | 2 | 2 | 1 | 3 | 2 | | | | 3 | | | | | | | | | | | | | | | | | | |
| C. sp. | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | |
| Cornuspira planorbis | 1 | | | | | 2 | 3 | | | | | | | | | | | | | | | | | | | | |
| Discorbis cf. columbiensis | 1 | | | | | | | | | | | | | | | | 4 | | | 4 | | | | | 2 | | 7 |
| D. williamsoni | | | 14 | | | | | | | | 4 | | | | | | | | | 7 | | 2 | 14 | 3 | 2 | 4 | |
| Ehrenbergina undulata | 1 | | | | 2 | | | | | | | 3 | | | | | | | | | | | | | | | |
| Elphidium advenum | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Eponides umbonatus and variants | | 2 | 3 | 3 | 2 | 2 | | | 2 | 5 | | | | | 9 | | | 5 | | | | | | | 7 | | 3 |
| Glomospira cf. gordialis | 6 | 7 | | | | | 17 | 4 | | | | | | | | | | | | | | | | | | | |
| Gyroidina lamarckiana | 2 | 2 | 3 | | | 2 | | | | | | | | | | | | | | | | | | | | | |
| G. orbicularis | 1 | | | | | | | | | 2 | | | | | | | | | | | | | | | | | |
| G. soldanii variant | | | | | 4 | | | | | | | | | | | | | | | | | | | | | | |
| Höglundina elegans | | 7 | 6 | | 33 | 8 | | | 16 | | 9 | 3 | 4 | 11 | | 12 | 4 | | | 4 | | 2 | | 1 | | | |
| Eggerella bradyi | | | | | | 4 | | | 2 | | | | | | | | | | | | | | | | 2 | 4 | 3 |
| Laticarinina pauperata | | | | 6 | | | 3 | | | 2 | | | | | | | | | | | | 2 | | | | 4 | |
| Miliolids | 6 | | 1 | 6 | | | 3 | | | 5 | | | | | 9 | 18 | | 10 | 5 | 13 | | 7 | | 1 | 4 | 4 | |
| Nodosaria sps. | | | | | | | | | | | | | | | | | | | | | | 2 | 5 | 50 | 20 | 8 | 7 |
| Nonion formosum | | | | | | | | | | | | | | 4 | | | 4 | | | | 6 | | | | | | |
| N. germanicum | | | | | | 2 | | | | | | 3 | | | | | | | | | | 5 | 5 | 1 | 2 | | |
| N. pompilioides | | | | 3 | | 2 | | | 2 | | 4 | | | | | | | | | | 6 | | | | 2 | | |
| Nonionella sloanii | 1 | | | | | | | | | | | | | | | 6 | 4 | | 5 | | | 2 | | | 7 | 4 | |
| Nummoloculina irregularis | 5 | 13 | 21 | 6 | 10 | 17 | 27 | 12 | 16 | 14 | 15 | 18 | 10 | 14 | 13 | 12 | 12 | 14 | | 4 | 6 | 7 | 14 | 2 | 9 | | 7 |
| Ophthalmidium inconstans | | 2 | 23 | 3 | 2 | 10 | 10 | 14 | | 17 | | 11 | 7 | | 9 | | 16 | 5 | 5 | 7 | 17 | 2 | 5 | 1 | | | |
| Osangularia cultur | | | | | 2 | | | | 5 | | | | 4 | | | | | 5 | | | | 2 | | | | | |
| Patellina corrugata | | | | 3 | | 2 | | | | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 2 | 7 | 3 | 3 | 4 | 2 | | 4 | 21 | 10 | | 7 | 4 | 11 | | | | | | | | | 5 | 3 | | | |
| Plectina apicularis | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | |
| Pleurostomella acuminata | | | | | | | | | | | | | | | 4 | | | | | | | | | | 4 | | |
| Epistominella exigua | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | |
| E. umbonifera | 7 | | 1 | | | 4 | | | | | | | | | | | | | | | | | | | | | |
| Pullenia bulloides | | 2 | | | | | | | 2 | | | | 4 | | | | 4 | | | 4 | | | | | | | |
| P. quinqueloba | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P. cf. riveroi | 5 | 2 | | | | | | | 2 | | | | | | | | | | 5 | | | | | | | | 3 |
| Pyrgo murrhina | 1 | 7 | 3 | 3 | 2 | | | | | 5 | | 3 | 14 | | | 12 | | 5 | | | | | | 3 | | 4 | |
| P. oblonga | | | | | | | | | | | | | | 4 | | 6 | | | | | | | | | | | |
| Quinqueloculina venusta | | 2 | | | | 2 | | | | 2 | | | 4 | | | | | 10 | | | | | | | | | |
| Q. cf. weaveri | 2 | 4 | | | 6 | 6 | 3 | 12 | | | | 7 | 4 | 14 | | | | 5 | | | | | | | 2 | 4 | |
| Robertina bradyi | 5 | 4 | 4 | 6 | 8 | 8 | 3 | 4 | 14 | 12 | | 22 | 4 | 4 | | 6 | | 19 | | 4 | 6 | 5 | | 4 | 9 | 8 | 3 |
| Robulus | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | |
| Rupertia stabilis | | | | | | | | | | | | | | | | | 4 | | | | | | | | | | |
| Sigmoilina schlumbergeri | 1 | 4 | | | | | | | 2 | | | | | | | | | | | | | | | | | | |
| Siphotextularia curta | 1 | | | | | | | | | | | | 4 | | | | | | | 4 | | | | | | | |
| S. rolshauseni | 1 | | | | | 2 | | 8 | | | | | 4 | | | | | | | | | | | 1 | | | |
| Spirophthalmidium acutimargo | | | | 3 | | | | | | 5 | 9 | | | | | | | 5 | | | | | | | 2 | | |
| Tretomphalus atlanticus | 7 | 4 | 3 | | 4 | 4 | | 4 | 3 | 2 | 15 | 3 | 4 | 4 | 4 | 12 | 8 | | 5 | | 12 | 12 | | 2 | 7 | | |
| Trochammina cf. advena | 7 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Triloculina tricarinata | | | 4 | 3 | | 6 | 3 | 12 | | 7 | | | 4 | 14 | | 6 | 12 | 19 | | | 6 | 2 | | 2 | 4 | | |
| Uvigerina auberiana and variant | 2 | | | 25 | 2 | 10 | | 18 | 2 | | 4 | 3 | 14 | | | 12 | 16 | | 62 | 38 | | 14 | 24 | 12 | 2 | 52 | 47 |
| Virgulina bradyi | | | | 3 | | | | | | | 15 | 11 | | | | | | | | | | | | | | | |
| V. complanata | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | |
| Valvulineria araucana | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | |

appear to contain a tropical fauna. Sample 110 at 1,069.5—1,070 cm. appears to have a mid-latitude assemblage, but only ten specimens were seen.

**Core 267.** This core is white in color and appears to be essentially pure calcium carbonate. All samples contain high populations of Foraminifera and the material may be called a *Globigerina* ooze, with considerable solution having occurred. The material of this core appears to be essentially all displaced from shoaler water than the depth at which it was collected. Several of the following shallow-water benthonic species are recorded from all but three of the core samples:

*Amphistegina lessonii*
*Angulogerina selseyensis*
*Bolivina globulosa*
*B. paula*
*B. pseudoplicata*
*B. pulchella*
*Bulimina mexicana*
*Cibicides* cf. *refulgens*
*Cornuspira planorbis*
*Discorbis* cf. *columbiensis*
*D. williamsoni*
*Elphidium advenum*
*Nonionella sloanii*

Since most or all of this core has been displaced from shallow water, it appears undesirable to attempt a chronology based upon shift of the modern planktonic assemblage.

Three fossil species are present. *Globigerina altispira* and *G. venezuelana* occur in significant

TABLE 26. Occurrences of Foraminifera in selected samples from Core 276 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 276 DEPTH- 4,852 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 2 | 7 | 12 | 14 | 18 | 26 | 28 | 33 | 38 | 49 | 54 | 59 | 63 | 68 | 71 | 73 | 76 | 90 | 94 | 112 | 117 | 122 | 126 | 129 | 134 | 139 | 147 |
| CM. FROM TOP OF CORE | 1-1.5 | 9.5-10 | 59.5-60 | 109.5-110 | 129.5-130 | 169.5-170 | 249.5-250 | 269.5-270 | 319.5-320 | 369.5-370 | 479.5-480 | 529.5-530 | 579.5-580 | 619.5-620 | 669.5-670 | 699.5-700 | 719.5-720 | 749.5-750 | 889.5-890 | 929.5-930 | 1109.5-1110 | 1159.5-1160 | 1209.5-1210 | 1249.5-1250 | 1279.5-1280 | 1329.5-1330 | 1379.5-1380 | 1459.5-1460 |
| PLANKTONIC POPULATION | 285 | 300 | 700 | 600 | 2,450 | 2,200 | 800 | 2,900 | 13,000 | 700 | 1,700 | 3,350 | 3,100 | 2,250 | 1,600 | | 1,000 | 3,600 | 650 | 1,600 | 1,400 | 2,650 | 4,300 | 2,450 | 2,350 | 1,900 | 1,320 | 4,500 |
| Globigerina bulloides | 3 | | 11 | 6 | 31 | 16 | 8 | 3 | 13 | 3 | 5 | 15 | 15 | 18 | 5 | | 16 | 13 | 3 | 10 | 10 | 17 | 36 | 17 | 15 | 10 | 18 | 31 |
| G. digitata | | | | | | | | | | | | | | | | | | | | | | | | | R | | | |
| G. eggeri | 3 | 7 | 12 | 18 | 7 | 13 | 6 | 4 | 3 | 21 | 15 | 5 | 13 | 14 | 6 | | 4 | 4 | 17 | 2 | 19 | 3 | 5 | 15 | 12 | 7 | 7 | 2 |
| G. inflata | 64 | 87 | 43 | 47 | 15 | 28 | 40 | 45 | 22 | 44 | 34 | 27 | 26 | 20 | 42 | | 18 | 22 | 45 | 20 | 1 | 3 | 11 | 34 | 34 | 55 | 49 | 6 |
| G. pachyderma | 4 | 5 | 3 | 5 | 1 | 3 | .5 | .5 | .2 | 7 | 4 | 1 | 5 | 1 | | | .8 | .7 | 2 | .3 | .6 | 2 | .6 | 5 | .7 | 2 | 2 | .4 |
| G quinqueloba | | | | | .3 | .4 | | | | | | | | | | | | | | | | | | | | | | |
| Globigerinella aequilateralis | 1 | | 4 | 1 | 3 | 3 | 2 | 1 | 2 | | 2 | 2 | | 3 | .5 | | .8 | 4 | .3 | .5 | | 1 | 3 | | .3 | | .3 | 2 |
| Globigerinita glutinata | 1 | | 1 | 1 | 3 | 2 | 2 | .3 | .7 | .3 | | 3 | 1 | 4 | .5 | | 2 | 2 | .3 | 2 | .8 | 3 | 5 | .7 | | .2 | .3 | 4 |
| Globigerinoides conglobata | 1 | | | .7 | | .7 | .5 | .5 | .2 | .3 | 2 | | 1 | .7 | .5 | | .8 | 1 | .3 | .5 | 1 | .6 | 1 | | .3 | | .3 | R |
| G. rubra | 7 | | 12 | 15 | 19 | 24 | 27 | 9 | 30 | 9 | 11 | 23 | 16 | 21 | 11 | | 20 | 27 | 8 | 27 | 20 | 25 | 27 | 18 | 19 | 12 | 14 | 28 |
| G. sacculifera | .7 | | 6 | 2 | 1 | 3 | .8 | 1 | 4 | 2 | .8 | 3 | 3 | 2 | 4 | | 3 | 2 | .3 | 5 | .6 | 2 | 2 | 4 | 2 | .4 | .6 | 3 |
| Globorotalia hirsuta | 3 | | .3 | 1 | .3 | | 2 | 7 | 5 | 8 | 16 | 4 | 7 | 1 | 15 | | 10 | 3 | 8 | 4 | 20 | 12 | .7 | | .3 | .8 | .3 | |
| G. menardii – tumida group | | | | .2 | | | | R | .2 | | 2 | .5 | .3 | .4 | .5 | | | 1 | 1 | 2 | | | | | | | | .7 |
| G. punctulata | | | | .7 | R | .4 | 2 | | .5 | .3 | | 2 | .8 | 5 | | | 3 | 4 | 1 | 11 | 2 | 9 | 2 | .3 | 8 | 6 | 4 | 7 |
| G. scitula | | | | | 3 | 1 | .3 | .3 | .2 | | | R | .8 | 1 | | | .4 | .7 | | .3 | .3 | 2 | 2 | | | | | 1 |
| G. truncatulinoides | 12 | 2 | 5 | 3 | 13 | 4 | 9 | 21 | 11 | 2 | 9 | 12 | 9 | 7 | 15 | | 20 | 13 | 13 | 16 | 20 | 19 | 2 | 5 | 7 | 6 | 4 | 13 |
| Orbulina universa | | | 2 | .2 | 3 | 1 | .3 | 1 | 1 | 2 | .5 | 2 | 1 | .7 | 2 | | .4 | 2 | .3 | .3 | 1 | 2 | .7 | 1 | 2 | .2 | .3 | 1 |
| Pulleniatina obliquiloculata | | | | | | | | .8 | .5 | | | | R | | | | | R | | 1 | 3 | .3 | .7 | | .3 | .2 | | .4 |
| Sphaeroidinella dehiscens | | | | | | | | | | .3 | | | | | | | | | | | | | | | | | | |
| BENTHONIC POPULATION | 40 | 95 | 140 | 60 | 65 | 80 | 55 | 90 | 160 | 40 | 100 | 70 | 100 | 110 | 80 | 600 | 35 | 85 | 90 | 45 | 105 | 60 | 50 | 50 | 110 | 85 | 105 | 65 |
| Cassidulina subglobosa | | 3 | 2 | 2 | 4 | 6 | 6 | 10 | 1 | 2 | 4 | 4 | 11 | 12 | 8 | .7 | 18 | 2 | 2 | 6 | 12 | 14 | 6 | 4 | 4 | 1 | 5 | 5 |
| Cibicides robertsonianus | | | | | | | | | 31 | | | | 1 | | | | | 1 | | | 2 | | | | 1 | | | 2 |
| C. sp. | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Eponides umbonatus and variants | 12 | 2 | 4 | 8 | 6 | 13 | 19 | 21 | 18 | 17 | 12 | 6 | 10 | 4 | 24 | 7 | 15 | 18 | 28 | 4 | 18 | 17 | 6 | 6 | 12 | 8 | 5 | 3 |
| Gyroidina orbicularis | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | |
| G. soldanii variant | | | 1 | | | | | | | | | 1 | | | | | | | | | | | | | 1 | | | |
| Eggerella bradyi | 7 | 2 | 2 | 2 | 4 | 9 | 7 | 5 | 4 | 5 | 1 | 11 | 1 | 2 | 5 | | 6 | 6 | 3 | 6 | 10 | 10 | 6 | 6 | 5 | 10 | 4 | 5 |
| Nonion formosum | | | | | | 1 | | 1 | 1 | | | | | 1 | | | 3 | 1 | | | 2 | 2 | | | | 1 | | |
| N. pompilioides | | 1 | 4 | 2 | 3 | 4 | 9 | 7 | | 5 | 3 | 1 | 1 | 4 | 3 | | 6 | 1 | | | 2 | 7 | 12 | 4 | 3 | 1 | | 5 |
| Planulina wuellerstorfi | 7 | | 1 | 2 | | 5 | 6 | 9 | 5 | 5 | 6 | 1 | 2 | 3 | 5 | 1 | 3 | 4 | | 2 | 1 | 2 | 2 | 2 | 3 | | 2 | 3 |
| Epistominella exigua | 29 | 28 | 37 | 15 | 9 | 9 | 7 | 10 | 14 | 26 | 15 | 21 | 20 | 20 | 5 | 19 | 6 | 7 | 23 | 9 | 6 | 22 | 28 | 2 | 7 | 4 | 31 | 25 |
| E. umbonifera | 39 | 61 | 41 | 53 | 63 | 37 | 35 | 23 | 44 | 17 | 47 | 30 | 42 | 39 | 39 | 70 | 21 | 38 | 27 | 40 | 23 | 10 | 22 | 49 | 41 | 52 | 47 | 22 |
| Pullenia bulloides | | 1 | 4 | 6 | 3 | 10 | 6 | 4 | 5 | 2 | 2 | 7 | 1 | 6 | 3 | | 6 | 11 | 1 | 19 | 12 | | 8 | 4 | 11 | 10 | 4 | 17 |
| P. quinqueloba | | | .7 | 3 | 1 | 5 | 4 | 5 | | | 3 | 1 | 4 | 3 | 3 | | 3 | 2 | 9 | | 1 | 7 | 2 | 14 | 5 | 7 | | 3 |
| P. sp. | | 1 | 1 | | | | 2 | 3 | | 5 | 4 | 10 | 2 | 2 | 3 | | 6 | 1 | 1 | | 3 | 2 | | 2 | 3 | 2 | 2 | 5 |
| Pyrgo murrhina | | 1 | .7 | | 1 | | | | | 2 | 1 | 1 | 1 | 1 | | | | 2 | 4 | 2 | | | | 4 | | | | |
| Quinqueloculina venusta | | | | | | | | | | 5 | | | | | 1 | | | | | | | | | | 1 | | | |
| Q. cf weaveri | | | | | | | | 1 | | | | | | | | | | | | | | | 2 | | 2 | 2 | | 5 |
| Robulus | | | | | | | | | 1 | 5 | | | | | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | 2 | | | 5 | | | | 1 | 4 | 2 | 3 | 3 | 2 | 1 | 3 | | 3 | 5 | | | 2 | 5 | 2 | 2 | 2 | 1 | | 3 |
| Spiroloculina sp. | | | | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| Textularia australis | | | | | | | | | | | | | | 2 | | | 3 | 1 | | 6 | 5 | 3 | 4 | | | | 1 | |
| Valvulineria humilis | 2 | | | 2 | 1 | 1 | | | 1 | | | 1 | 1 | | | | | | | | 3 | | | | | | | |
| Virgulina bradyi | | | | | | | | | | 2 | | | | 1 | | | | | | | | | | | | | | |
| V. complata | | | .7 | | | | | | | | | | | 1 | | | | | 1 | | | | | | | | 1 | |

frequencies from 610 cm. to at least 950 cm. *Globorotalia* sp. 2 occurs in a few samples from 90 cm. to the bottom of the core.

**Core 276.** This and the succeeding cores described here are from mid-latitude areas, 30° N Lat. to approximately 42° N Lat. The modern fauna is thus a mid-latitude assemblage; differences from this fauna and one representing areas of colder surface water are difficult to ascertain. In this core these differences appear to be indicated largely by variations in frequency of *Globigerina pachyderma* and *Globorotalia truncatulinoides.* Low percentages of typically low-latitude species such as *G. menardii, G. tumida,* and *Pulleniatina obliquiloculata* probably are to be expected in this area because of the water circulation pattern and generally are not considered indicators.

According to our interpretation there are at least four shifts from mid-latitude assemblages to assemblages which appear to represent somewhat higher-latitude conditions.

**Core 278.** The fauna in the upper 80 cm. of this core is so fragmented by intense solution that it was not counted. The uppermost sample studied, at 90 cm., contains a colder-than-modern fauna, and there are three additional colder-water assemblages, separated by the normal mid-latitude fauna, in the lower core sections. The indicative species for the modern, mid-latitude assemblage in this core appear to be *Globorotalia truncatulinoides, Pulleniatina obliquiloculata, Globorotalia menardii-tumida,* and *Globigerinoides conglobata.* Indicators for the colder assemblage appear to be relatively high frequencies of *Globigerina pachyderma* and *G. bulloides* together with low frequencies or absence of the mid-latitude indicators.

**Core 279.** The upper core fauna appears to represent somewhat colder surface water conditions than the surface sample collected at the same station. There appear to be nine shifts to colder-water faunas in the 19 m. length of this core. Criteria for differentiating the faunas are the same as described above.

TABLE 27. Occurrences of Foraminifera in selected samples from Core 278 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 278 DEPTH-5,520 M. | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 10 | 13 | 14 | 46 | 54 | 58 | 59 | 63 | 88 | 102 | 134 | 160 |
| CM. FROM TOP OF CORE | 89.5-90 | 119.5-120 | 129.5-130 | 449.5-450 | 529.5-530 | 569.5-570 | 579.5-580 | 619.5-620 | 869.5-870 | 1009.5-1010 | 1329.5-1330 | 1489.5-1490 |
| PLANKTONIC POPULATION | 540 | 10,000 | 5,000 | 550 | 1,000 | 1,200 | 1,750 | 1,200 | 800 | 2,050 | 500 | 2,860 |
| Globigerina bulloides | 35 | 23 | 3 | 5 | 10 | 16 | 41 | 8 | 10 | 10 | 2 | 11 |
| G. digitata | | | | | | 1 | | | | | .4 | |
| G. eggeri | 16 | 13 | 7 | 13 | 8 | 6 | 5 | 12 | 10 | 3 | 17 | 6 |
| G. inflata | 8 | 22 | 38 | 47 | 29 | 26 | 15 | 39 | 44 | 35 | 42 | 20 |
| G. pachyderma | 4 | 2 | | .2 | 1 | | | 1 | .5 | 2 | 4 | .3 |
| Globigerinella aequilateralis | .7 | 1 | .6 | 2 | 2 | 2 | 2 | 2 | .2 | 1 | 1 | 1 |
| Globigerinita glutinata | 7 | 1 | | .4 | 1 | .3 | 3 | | 1 | 3 | .8 | 2 |
| Globigerinoides conglobata | | | 2 | .5 | | .3 | | | 1 | .4 | | .8 |
| G rubra | 23 | 24 | 5 | 14 | 34 | 24 | 25 | 31 | 15 | 22 | 21 | 29 |
| G sacculifera | | 3 | 1 | 11 | 6 | 1 | 1 | 2 | 2 | 6 | 2 | 4 |
| Globorotalia hirsuta | 1 | 2 | 5 | | 1 | 2 | .7 | | 2 | 3 | 5 | 1 |
| G menardii-tumida group | | | .6 | | | | | | | 1 | .8 | .3 |
| G punctulata | 4 | 4 | 10 | .2 | .2 | 1 | .2 | .3 | 4 | 1 | | 2 |
| G. scitula | 2 | .5 | | | | .3 | 2 | | | | | 3 |
| G truncatulinoides | 2 | 3 | 26 | 5 | 6 | 13 | 4 | 3 | 10 | 11 | 5 | 19 |
| Orbulina universa | 1 | 2 | .6 | 2 | 3 | 6 | .7 | 2 | .2 | .6 | 2 | 2 |
| Pulleniatina obliquiloculata | | | 1 | | | .3 | | | | .8 | | .3 |
| Sphaeroidinella dehiscens | | | .3 | | | | | | | | | |
| BENTHONIC POPULATION | 35 | 400 | 60 | 5 | 15 | 30 | 25 | 30 | 25 | 50 | 30 | 40 |
| Cassidulina subglobosa | 6 | 7 | 5 | | | | | 10 | 8 | 9 | | 10 |
| Cibicides robertsonianus | | | 2 | | | | | | | | | 3 |
| Eponides tumidulus | | | | | | 7 | | | | 2 | | |
| E umbonatus and variants | 11 | 14 | 25 | | 23 | 14 | 8 | 3 | 17 | 13 | 23 | 18 |
| Gyroidina orbicularis | | | | | | | | | | 2 | | |
| G. soldanii variant | | .5 | 2 | | | | | | | | | |
| Eggerella bradyi | 3 | 6 | 3 | | 6 | 14 | 8 | 43 | 21 | 2 | 10 | 3 |
| Nonion pompilioides | 3 | 5 | 9 | | 6 | | 4 | | 17 | 2 | 10 | |
| Planulina wuellerstorfi | | 3 | 14 | 40 | 18 | 14 | 8 | 13 | 13 | 2 | 6 | 8 |
| Epistominella exigua | 30 | 13 | 5 | | 6 | | | | 4 | 17 | 13 | 3 |
| E umbonifera | 22 | 28 | 23 | | 18 | 11 | 4 | 10 | 8 | 30 | 3 | 29 |
| Pullenia bulloides | 6 | 9 | 5 | | | | | | | 15 | | 3 |
| P quinqueloba | 20 | 6 | 2 | 60 | 23 | 25 | 33 | 17 | | 2 | 16 | 16 |
| P sp | | 4 | 2 | | | | 8 | | 4 | | 6 | |
| Pyrgo murrhina | | 4 | | | | | | | | | 3 | |
| Quinqueloculina venusta | | | | | | 4 | | | | | | |
| Q cf. weaveri | | | 3 | | | | | | | 2 | | |
| Robulus | | | | | | 4 | | 3 | | | 3 | |
| Siphotextularia rolshauseni | | .5 | | | | | 13 | | 8 | 2 | 3 | 8 |
| Textularia australis | | .5 | 2 | | | | | | | | | |
| Valvulineria humilis | | | | | | 7 | 13 | | | | | |
| Virgulina bradyi | | 1 | | | | | | | | | 3 | |

**Core 280.** There are nine faunas in this core which are interpreted as representing somewhat cooler surface water conditions than the modern mid-latitude assemblage. This is based largely on the lower frequencies of *Globorotalia truncatulinoides* and increase of *Globigerina pachyderma.* The top sample of the core contains *Bolivina subaenariensis* and *Bulimina exilis,* both of which are shallow-water species. The cooler-than-present faunas are interbedded with warm-water faunas.

TABLE 28. Occurrences of Foraminifera in selected samples from Core 279 in percent of total population. Planktonic and benthonic populations computed separately.

| | | | | | | | | CORE 279 | | | | | | | | | | | | | | | | | | | | | DEPTH-4,663M. | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 3 | 7 | 12 | 14 | 19 | 23 | 27 | 32 | 33 | 37 | 39 | 44 | 47 | 49 | 53 | 58 | 60 | 64 | 67 | 72 | 77 | 80 | 81 | 86 | 91 | 96 | 100 | 102 | 105 | 109 | 113 | 118 | 123 | 125 | 126 | 127 | 129 | 131 | 138 | 143 | 147 | 152 | 156 | 161 | 168 | 171 | 176 | 180 | 185 | 190 |
| CM. FROM TOP OF CORE | 1-1.5 | 18.5-19 | 59.5-60 | 109.5-110 | 129.5-130 | 179.5-180 | 219.5-220 | 259.5-260 | 309.5-310 | 319.5-320 | 359.5-360 | 379.5-380 | 429.5-430 | 459.5-460 | 479.5-480 | 519.5-520 | 569.5-570 | 589.5-590 | 629.5-630 | 659.5-660 | 709.5-710 | 759.5-760 | 789.5-790 | 799.5-800 | 849.5-850 | 899.5-900 | 949.5-950 | 989.5-990 | 1009.5-1010 | 1039.5-1040 | 1077-1077.5 | 1118.5-1119 | 1171-1171.5 | 1219.5-1220 | 1239.5-1240 | 1249.5-1250 | 1258.5-1259 | 1279.5-1280 | 1299.5-1300 | 1369.5-1370 | 1419.5-1420 | 1459.5-1460 | 1509.5-1510 | 1549.5-1550 | 1589.5-1590 | 1659.5-1660 | 1689.5-1690 | 1739-1739.5 | 1779.5-1780 | 1829.5-1830 | 1879.5-1880 |
| PLANKTONIC POPULATION | 1,200 | 2,800 | 7,550 | 6,250 | 5,800 | 3,850 | 6,250 | 3,700 | 4,800 | 6,700 | 575 | 5,800 | 4,150 | 5,500 | 7,350 | 7,150 | 3,100 | 2,900 | 2,100 | 3,550 | 1,400 | 650 | 1,300 | 5,500 | 3,300 | 5,100 | 600 | 4,150 | 2,600 | 35,000 | 1,000 | 3,400 | 400 | 2,800 | 3,900 | 5,500 | 2,700 | 1,800 | 3,600 | 2,300 | 9,300 | 3,250 | 7,200 | 9,300 | 8,500 | 10,200 | 8,600 | 5,600 | 7,500 | 4,500 | 3,750 |
| Candeina nitida | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .3 | | | | | | | | | | | | | | | | | | | | | | |
| Globigerina bulloides | 12 | 6 | 9 | 21 | 16 | 10 | 6 | 5 | 15 | 19 | 5 | 22 | 14 | 11 | 18 | 22 | 14 | 19 | 7 | 9 | 3 | | 5 | 13 | 7 | 17 | 2 | 12 | 12 | 13 | 14 | 19 | 18 | 20 | 20 | 30 | 19 | 5 | 21 | 14 | 30 | 13 | 25 | 9 | 7 | 33 | 13 | 32 | 40 | 30 | 22 |
| G digitata | | .6 | | | | | | .2 | | | | | | | | | | | | | | | | | | | .3 | .8 | | | | | | | | | | | | | | | | | | | | | | | |
| G eggeri | 25 | 10 | 8 | 10 | 7 | 21 | 31 | 26 | 17 | 11 | 16 | 10 | 10 | 14 | 8 | 12 | 10 | 15 | 12 | 9 | 29 | 28 | 19 | 6 | 6 | 8 | 13 | 8 | 12 | 10 | 13 | 8 | 13 | 15 | 7 | 10 | 17 | 12 | 4 | 9 | 8 | 7 | 10 | 12 | 9 | 6 | 13 | 8 | 8 | 4 | 8 |
| G inflata | 34 | 53 | 39 | 26 | 31 | 39 | 31 | 25 | 28 | 29 | 55 | 27 | 31 | 26 | 23 | 18 | 31 | 29 | 42 | 39 | 47 | 53 | 56 | 31 | 31 | 35 | 64 | 26 | 41 | 38 | 44 | 40 | 40 | 31 | 24 | 19 | 29 | 74 | 29 | 42 | 12 | 34 | 28 | 36 | 47 | 22 | 48 | 21 | 22 | 15 | 31 |
| G pachyderma | 2 | 2 | | | .3 | 3 | 3 | 1 | .7 | 1 | | 1 | | 2 | .4 | .7 | 1 | .5 | .8 | .4 | 3 | .6 | 1 | .3 | | .3 | .3 | .4 | .3 | | 1 | | 1 | .3 | .4 | 2 | 3 | 1 | .4 | 1 | .7 | | .7 | .3 | | 2 | 1 | .6 | .2 | .4 | .2 |
| G quinqueloba | | | | | | | | | | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Globigerinella aequilateralis | R | 1 | 1 | .5 | .8 | .4 | .8 | 1 | .7 | 1 | .7 | .8 | .4 | 4 | 2 | 2 | .5 | .3 | .4 | 1 | | | | .6 | .7 | .6 | | 2 | 3 | 4 | .2 | .7 | .5 | 3 | 2 | 2 | 1 | | 2 | .7 | .7 | 2 | 1 | 1 | .8 | 2 | .6 | .6 | 2 | .2 | 1 |
| Globigerinita glutinata | .7 | .3 | 1 | .5 | 3 | 2 | | 1 | .7 | 1 | .7 | .6 | 5 | 2 | 2 | 2 | 2 | 2 | | 2 | | | | | 1 | 1 | | 2 | 2 | | .6 | .2 | | 1 | .4 | 1 | 1 | | .7 | .7 | .7 | .7 | .7 | .3 | .8 | 2 | .6 | 1 | 3 | 3 | 2 |
| Globigerinoides conglobata | | .6 | .4 | 1 | 1 | 1 | .5 | 1 | 1 | .2 | | .6 | 2 | | 1 | .4 | .8 | .8 | 2 | .7 | .8 | 2 | 2 | | | .6 | 1 | .8 | .3 | .2 | .4 | .7 | | .3 | | | .6 | .2 | 1 | 2 | | 1 | .2 | .2 | .4 | .2 | | | | .4 | .4 |
| G rubra | 19 | 13 | 9 | 12 | 15 | 11 | 6 | 16 | 12 | 9 | 7 | 15 | 13 | 12 | 15 | 18 | 18 | 17 | 9 | 18 | 2 | .6 | 7 | 20 | 15 | 16 | 4 | 20 | 16 | 17 | 10 | 10 | 14 | 17 | 18 | 14 | 16 | 4 | 14 | 10 | 18 | 17 | 13 | 15 | 9 | 10 | 11 | 17 | 8 | 21 | 15 |
| G sacculifera | 2 | .3 | 2 | 3 | 4 | 2 | .5 | 1 | 2 | 2 | 1 | 3 | 2 | 3 | 3 | 6 | 2 | 1 | .4 | 3 | .3 | | 1 | 4 | 1 | 1 | | 2 | 3 | 6 | 2 | 2 | 2 | 1 | 4 | 2 | 1 | .5 | 4 | 3 | 2 | 4 | 2 | 2 | 2 | 3 | 1 | 2 | 2 | 6 | 6 |
| Globorotalia hirsuta | 1 | 3 | 7 | 7 | 6 | 4 | 15 | 13 | 1 | 5 | 3 | 4 | 6 | 4 | 7 | 5 | 9 | 3 | 8 | 4 | .3 | .6 | 2 | 2 | 5 | 3 | 10 | 3 | .3 | 1 | .2 | .7 | .5 | | 4 | .4 | .3 | | .7 | .3 | | | 3 | .2 | | 3 | | | .4 | | |
| G menardii-tumida group | | R | .7 | R | 1 | | .3 | | 1 | .2 | .7 | 3 | | 1 | 1 | .2 | .3 | 2 | .4 | 1 | | | .6 | .6 | .5 | .6 | 1 | 2 | 2 | .7 | .6 | .5 | R | .6 | | .6 | R | R | .4 | R | 1 | 2 | R | .3 | R | | .4 | | | | 1 |
| G. punctulata | .3 | 1 | 1 | .5 | .6 | .4 | 1 | .2 | 3 | 4 | 3 | 5 | 2 | 3 | .7 | .7 | .5 | 2 | 3 | 4 | 10 | 7 | | 2 | 10 | 5 | 1 | 7 | 4 | 4 | 5 | 9 | 3 | 4 | 8 | 5 | 2 | .7 | 10 | 8 | 12 | 8 | 9 | 14 | 9 | 6 | 3 | 6 | 4 | 2 | 5 |
| G scitula | 1 | | .4 | .5 | R | | | .2 | 2 | 1 | | .8 | 1 | 1 | .2 | 2 | 1 | 2 | .4 | .2 | | | | .6 | | 2 | | .4 | .6 | .7 | .4 | 1 | .5 | 1 | 5 | 3 | .6 | | .4 | | 3 | .2 | 1 | .5 | .8 | .8 | .6 | 4 | 2 | .5 | 2 |
| G truncatulinoides | 2 | 7 | 20 | 18 | 13 | 4 | 6 | 7 | 12 | 14 | 4 | 7 | 12 | 13 | 17 | 10 | 8 | 5 | 14 | 9 | 4 | 7 | 4 | 18 | 21 | 8 | 4 | 15 | 2 | 3 | 7 | 6 | 8 | 6 | 5 | 8 | 6 | 2 | 10 | 7 | 9 | 8 | 6 | 7 | 13 | 6 | 7 | 6 | 3 | 16 | 4 |
| Orbulina universa | | 1 | 1 | 1 | .8 | .2 | .5 | 1 | 2 | 2 | 1 | 1 | 2 | 3 | 2 | 2 | 2 | 1 | .8 | .7 | 2 | | . | 2 | .5 | .6 | .3 | | 1 | 2 | 1 | 2 | .5 | 1 | 3 | 2 | 2 | .2 | 1 | 1 | 1 | 2 | .7 | 1 | 2 | 2 | 2 | .6 | 3 | 1 | 1 |
| Pulleniatina obliquiloculata | | | .4 | | .8 | | | | | | | .3 | | | | | | | | | | | .6 | | .2 | .3 | R | 1 | | | | | | | .8 | .1 | R | | 1 | .7 | | R | .2 | .3 | .4 | | .2 | 1 | .2 | .5 | .2 |
| Sphaeroidinella dehiscens | | | | | | | | | | | | | | | | | | | | | | | .6 | | | | | | | | | .5 | | | | .1 | .3 | | .2 | | .2 | .2 | | .3 | .4 | R | | .3 | | | |
| BENTHONIC POPULATION | 55 | 120 | 150 | 130 | 200 | 75 | 175 | 115 | 120 | 155 | 65 | 135 | 115 | 120 | 140 | 155 | 165 | 210 | 145 | 90 | 245 | 140 | 140 | 140 | 90 | 60 | 75 | 70 | 110 | 680 | 130 | 95 | 5 | 95 | 60 | 90 | 90 | 70 | 110 | 80 | 185 | 65 | 75 | 80 | 115 | 125 | 180 | 100 | 75 | 70 | 65 |
| Bolivina pseudopunctata | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cassidulina subglobosa | 8 | 8 | 15 | 9 | 9 | 12 | 6 | 8 | 12 | 11 | 7 | 13 | 9 | 10 | 12 | 20 | 9 | 7 | 13 | 5 | 5 | 5 | 9 | 10 | 8 | 6 | 7 | 7 | 7 | 9 | 7 | 19 | | 3 | 12 | 7 | 10 | 15 | 12 | 12 | 12 | 8 | 11 | 7 | 5 | 15 | 8 | 13 | 16 | 11 | 15 |
| Cibicides robertsonianus | 2 | | 1 | .8 | | | | | 3 | .6 | 1 | | 2 | .8 | 3 | | | | | | | | 2 | 2 | | | 3 | | | 1 | | 1 | | | | 5 | 1 | 1 | | | 2 | 5 | 1 | | 1 | | | 1 | 2 | | 2 |
| Ehrenbergina trigona | | | | | | | .6 | | | 1 | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | | | |
| Eponides tumidulus | | | | .8 | 1 | | | | | .6 | 1 | | | 2 | .7 | .6 | .6 | | 1 | | | | | .7 | | | | | | | .8 | | 33 | | | | 1 | 3 | | 1 | .5 | | 1 | | | | | | | | |
| E umbonatus and variants | 15 | 14 | 20 | 18 | 23 | 15 | 25 | 16 | 32 | 10 | 13 | 24 | 19 | 21 | 11 | 13 | 9 | 22 | 21 | 14 | 20 | 17 | 23 | 35 | 23 | 16 | 22 | 16 | 31 | 21 | 8 | 20 | | 27 | 22 | 18 | 25 | 19 | 21 | 22 | 12 | 29 | 28 | 15 | 40 | 14 | 33 | 33 | 30 | 34 | 28 |
| Gyroidina lamarckiana | | | | | | | | | | 1 | | | | | | 1 | | | | | | | .7 | | | | | 1 | | | | | | | | | | | | 1 | | | | | | .8 | | | | | |
| G. orbicularis | | .8 | | .8 | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | 2 | | 2 | | | | | | | 1 | | | | | | | | | | | | |
| G soldanii variant | | | 2 | 2 | | 1 | 2 | | | | | .7 | 2 | | 1 | | | .5 | .7 | | | | 1 | 1 | | | | 1 | | | .8 | | | | | | 3 | | | 6 | | | 1 | 4 | 2 | 2 | | | | | 2 |
| Eggerella bradyi | 2 | 8 | 12 | 14 | 4 | 5 | 2 | 3 | 2 | 4 | 12 | 4 | 9 | 7 | 2 | 3 | 4 | 3 | 8 | 13 | 12 | | 5 | 4 | 8 | 4 | 4 | 6 | 2 | 9 | 4 | 5 | | 4 | 10 | 7 | 10 | 3 | 13 | 4 | 5 | 8 | 4 | 6 | 7 | 10 | 4 | 4 | | 13 | 6 |
| Nonion formosum | | | 1 | 2 | 1 | | .6 | | 3 | 3 | | 2 | 2 | | 1 | | .6 | | | | | | | | 1 | | | | 1 | 2 | | 2 | | | 5 | 1 | 1 | | 1 | 1 | .5 | 3 | 1 | 1 | 1 | 2 | 2 | | 1 | | |
| N. pompilioides | | 7 | 3 | 4 | 5 | 1 | 7 | 4 | 3 | 3 | 4 | 4 | 1 | | 1 | 2 | 3 | 2 | 6 | 1 | 2 | | 1 | 1 | | 2 | 4 | 1 | 2 | 6 | 3 | 2 | | 4 | 3 | 5 | 4 | | 4 | 6 | 3 | 3 | 7 | 5 | 3 | 3 | 5 | 2 | 4 | 1 | |
| Planulina wuellerstorfi | 9 | 7 | 7 | 13 | 12 | 15 | 10 | 11 | 6 | 7 | 3 | 7 | 8 | 3 | 8 | 9 | 10 | 6 | 7 | 8 | 6 | 1 | 9 | 5 | 12 | 10 | 11 | 4 | 3 | 7 | 6 | 6 | 17 | 11 | 5 | 5 | 1 | 6 | 4 | 4 | 4 | 9 | 4 | 11 | 4 | 4 | 8 | 12 | 3 | 7 | 8 |
| Epistominella exigua | 26 | 15 | 8 | 5 | 6 | 23 | 13 | 16 | 5 | 6 | 30 | 7 | 4 | 2 | 9 | 10 | 7 | 15 | 9 | 7 | 4 | 26 | 24 | 9 | 6 | 16 | 8 | 12 | 7 | 4 | 5 | 6 | 33 | 1 | 10 | 11 | 9 | 1 | 5 | 3 | 11 | 6 | 4 | 5 | 1 | 6 | 4 | 1 | | 4 | 3 |
| E. umbonifera | 17 | 24 | 18 | 19 | 18 | 11 | 15 | 23 | 17 | 12 | 12 | 8 | 20 | 31 | 24 | 13 | 28 | 34 | 15 | 35 | 17 | 40 | 17 | 15 | 18 | 18 | 34 | 26 | 18 | 9 | 21 | 20 | 17 | 27 | 10 | 13 | 8 | 28 | 16 | 15 | 11 | 12 | 16 | 30 | 17 | 18 | 14 | 10 | 22 | 11 | 12 |
| Pullenia bulloides | 9 | 6 | 5 | 5 | 4 | 4 | 6 | 7 | 8 | 9 | 3 | 8 | 10 | 12 | 10 | 4 | 12 | 2 | 8 | 10 | .8 | 1 | .7 | 4 | 14 | 2 | 3 | 14 | 8 | 6 | 8 | 4 | | 6 | 5 | 8 | 4 | 9 | 7 | 5 | 10 | 6 | 13 | 11 | 9 | 10 | 7 | 14 | 9 | 11 | 11 |
| P. quinqueloba | | | | | 3 | | | | | .6 | 6 | | 2 | 3 | 3 | 3 | 2 | 1 | 2 | 1 | 2 | .7 | 3 | 2 | | 2 | | 1 | 3 | 1 | | 4 | | 5 | 3 | 1 | 4 | 1 | 1 | 1 | 3 | 3 | | | 1 | 7 | 1 | | 1 | 1 | 3 |
| P sp. | 2 | 4 | 1 | 2 | 5 | 3 | 3 | 4 | | 2 | 3 | 2 | 1 | 2 | 3 | .6 | 1 | 1 | 3 | | .8 | 1 | 3 | .7 | 1 | 2 | | 1 | 2 | 1 | .8 | 1 | | 2 | 3 | 1 | 3 | 1 | 2 | 1 | | | | 2 | 1 | 2 | 2 | 1 | 3 | 4 | |
| Pyrgo murrhina | 2 | .8 | 5 | 3 | 2 | 4 | 4 | 3 | 4 | 1 | 1 | 3 | 5 | .8 | | 3 | .6 | 1 | 1 | 2 | 13 | .7 | .7 | | | 2 | 1 | | 2 | 6 | .8 | 1 | | 3 | 3 | | 1 | 6 | 4 | 1 | .5 | 2 | 1 | | 1 | .8 | 3 | 2 | | | 3 |
| Quinqueloculina venusta | | 2 | | | | | .6 | | | .6 | | .7 | 1 | | .7 | | | | .7 | | | .7 | | | | | | | | | | | | 1 | | 3 | | | | 1 | | | | | | | .5 | | 1 | | 2 |
| Q. cf weaveri | | | | .8 | 1 | | | | | 2 | | | 1 | | | .6 | 1 | | | | | | | | | | | 3 | 1 | | | 1 | | | | 1 | 1 | | 2 | | 1 | 3 | 3 | 1 | 1 | .8 | .5 | 4 | 1 | | 2 |
| Robulus | | | | | | | | | | | | | | | | | | | | | | .7 | | .7 | | | | 1 | | | | | | | 2 | | 1 | 1 | | | | | | | | | | | | | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 1 | | | | | 1 | | | | | | | | | | | | | | |
| Siphotextularia rolshauseni | | 2 | 1 | 2 | 3 | 3 | 2 | 2 | .8 | 6 | | 1 | | 2 | 4 | 4 | 3 | 1 | 2 | | 3 | 2 | .7 | .7 | | | | | 1 | 1 | | | | 2 | | 1 | | 1 | 3 | 1 | | 3 | 1 | | 2 | 2 | 2 | 1 | 5 | | 2 |
| Textularia australis | | | | | | | | | .8 | 3 | | 1 | 6 | | 3 | 9 | 6 | 3 | 1 | | .8 | | | | 2 | 2 | | 1 | 1 | | 3 | | | | 2 | | 1 | 3 | 1 | 5 | 2 | 2 | 3 | | 2 | 2 | 1 | | | | 3 |
| Uvigerina hollicki | 4 | 2 | .7 | | | | .6 | | 5 | 16 | | 10 | | 2 | 1 | 1 | | | | 2 | 2 | | | 8 | 3 | 14 | 3 | 1 | 12 | 13 | 33 | 4 | | 3 | 5 | 13 | 10 | | 4 | 6 | 21 | | | 1 | 3 | | 5 | | | | |
| Valvulineria humilis | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina advena | | | | | .5 | | | | | | | .7 | | | | | | | | | 4 | 1 | | | | | | | | | | | | | | 1 | | | | 1 | | | | | | | | | | | |
| V bradyi | | | | | | | 1 | 2 | | | 1 | .7 | | | | | .6 | .5 | | | 6 | | .7 | | 2 | 2 | | | | | | | | | | | | | | | .5 | | | | | | | 2 | | | |
| V complanata | | | | | | | | | | .6 | | | | | | | | | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

TABLE 29. Occurrences of Foraminifera in selected samples from Core 280 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 280 DEPTH-4,256 M.

| SAMPLE | 1 | 4 | 10 | 14 | 18 | 22 | 25 | 29 | 33 | 35 | 37 | 38 | 41 | 46 | 47 | 51 | 57 | 58 | 62 | 64 | 70 | 71 | 76 | 79 | 81 | 82 | 87 | 90 | 95 | 98 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 1.5-2 | 29.5-30 | 89.5-90 | 129.5-130 | 169.5-170 | 209.5-210 | 239.5-240 | 279.5-280 | 317.5-318 | 339.5-340 | 359.5-360 | 369.5-370 | 399.5-400 | 449.5-450 | 459.5-460 | 499.5-500 | 559.5-560 | 569.5-570 | 609.5-610 | 629.5-630 | 689.5-690 | 699.5-700 | 749.5-750 | 779.5-780 | 799.5-800 | 809.5-810 | 859.5-860 | 889.5-890 | 939.5-940 | 969.5-970 |
| PLANKTONIC POPULATION | 8,500 | 4,600 | 1,000 | 700 | 1,700 | 2,350 | 3,100 | 4,200 | 3,900 | 2,900 | 2,200 | 500 | 5,100 | 1,700 | 7,800 | 3,600 | 6,250 | 3,100 | 8,200 | 3,900 | 4,900 | 5,200 | 6,150 | 1,870 | 6,250 | 3,300 | 6,000 | 2,900 | 7,350 | 4,650 |
| Candeina nitida |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Globigerina bulloides | 20 | 22 | 15 | 15 | 20 | 32 | 36 | 39 | 38 | 43 | 43 | 8 | 24 | 7 | 31 | 21 | 18 | 29 | 18 | 19 | 24 | 18 | 18 | 6 | 12 | 13 | 22 | 17 | 26 | 24 |
| G. digitata |  |  |  |  |  |  |  | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  |  |  |  |
| G. eggeri | 3 | 8 | 4 | 12 | 13 | 12 | 13 | 12 | 12 | 15 | 20 | 20 | 6 | 25 | 6 | 10 | 12 | 20 | 21 | 39 | 25 | 24 | 26 | 14 | 5 | 15 | 24 | 11 | 11 | 15 |
| G. inflata | 33 | 40 | 60 | 56 | 47 | 25 | 31 | 18 | 17 | 20 | 20 | 67 | 33 | 52 | 19 | 33 | 31 | 26 | 32 | 19 | 25 | 19 | 36 | 59 | 39 | 28 | 24 | 22 | 20 | 17 |
| G. pachyderma | 3 | 1 | .8 | 4 | 1 | 2 | 3 | 2 | 2 | 3 | 4 | 5 | 2 | 4 | .6 | 1 | 4 | 3 | 2 | 4 | 4 | 2 | 2 |  | .5 | .4 | 6 | 1 | 1 | 2 |
| G. quinqueloba |  |  |  |  |  |  |  |  | R |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .3 |  |  |  |  |  |
| Globigerinella aequilateralis | 3 | 2 | .4 | 1 | .7 | 1 | 1 |  | 1 | .6 |  | .4 |  |  | .8 | .7 | 2 | .5 | .8 | .4 | .3 | 1 | .5 | .4 | 2 | 2 | 1 | 2 | .7 | 2 |
| Globigerinita glutinata |  |  |  | .3 |  |  |  | 1 | 3 | .6 |  |  | 2 |  | 2 | .7 | 3 | 3 |  | .6 | .3 | 2 | 2 | 1 | 1 | 3 | 2 | 2 | 3 | 3 |
| Globigerinoides conglobata | R | .8 |  | .3 | .2 | R | .3 | R | .4 | .3 | .4 |  | .3 | .5 | .8 | 2 | .3 | .3 |  | .2 | .7 | .3 | .8 | .4 | .5 | .4 | .8 | 1 |  |  |
| G. rubra | 16 | 15 | 13 | 7 | 14 | 16 | 9 | 16 | 15 | 12 | 7 | 4 | 14 | 7 | 16 | 13 | 14 | 12 | 7 | 10 | 10 | 14 | 5 | 5 | 10 | 9 | 7 | 12 | 12 | 10 |
| G. sacculifera | 2 | 2 | 2 | 1 | 1 | 2 | .8 | .4 | 1 | .6 | .4 |  | 2 |  | .6 | 1 | 3 | 1 | 2 | .4 | .3 | .6 | 2 | 1 | 4 | 2 | 1 | 3 | 5 | 2 |
| Globorotalia hirsuta | 8 | 1 | .4 |  |  |  | .3 | 3 | .6 | R | 1 | 5 | 5 | 1 | 3 | 3 | 4 | 2 | 7 | 3 | 5 | 10 | 1 | 2 | 13 | 9 | 1 | 7 | 4 | 3 |
| G. menardii | R |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. menardii – tumida group | | R |  |  |  |  |  |  |  |  |  |  | R |  | R | .4 | R |  |  |  |  | R | .3 |  |  | 4 | R | R | R | .3 |
| G. punctulata |  |  |  |  | R |  |  |  |  | .3 |  |  | .3 | .5 | .6 | 2 | 1 | .5 |  | .2 |  | 2 | .3 | .4 | 2 | 3 | .8 | 2 | 1 | 3 |
| G. scitula | .3 | .5 |  | .6 | R | 6 | 2 | 5 | 7 | 3 | .4 |  | 3 |  | 3 | .2 | 1 | 2 | .4 |  | .3 | 1 | 2 |  | .5 | 2 | 1 | 1 | 2 | 5 |
| G. truncatulinoides | 9 | 4 | 4 |  | 2 | 2 | 2 | 2 | 3 | 2 | 2 | .8 | 10 | 3 | 13 | 12 | 5 | 1 | 6 | 3 | 4 | 7 | 3 | .6 | 8 | 11 | 6 | 15 | 10 | 10 |
| Orbulina universa | 3 | 3 | .8 | 2 | .5 | 1 | 1 | .8 | 1 | .6 | .4 |  | .3 | .5 | .8 | 1 | 3 | .8 | 1 | 1 | 2 | 1 | 2 | 4 | 3 | 2 | 2 | 2 | 2 | 2 |
| Pulleniatina obliquiloculata | .3 |  |  |  |  |  |  |  |  |  |  |  | .3 |  | .2 |  | .3 |  |  |  |  |  |  |  | .3 | .2 |  |  | .4 |  |
| Sphaeroidinella dehiscens |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .2 |  |  |  |  |  |  |  |  |  | .6 | .4 |  |  | R |  |
| BENTHONIC POPULATION | 65 | 45 | 35 | 20 | 50 | 55 | 70 | 45 | 40 | 50 | 45 | 35 | 95 | 120 | 130 | 90 | 80 | 30 | 30 | 60 | 80 | 60 | 80 | 90 | 130 | 90 | 70 | 75 | 170 | 120 |
| Anomalina sp |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | .8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bolivina pseudopunctata |  |  |  |  |  |  | 3 |  |  |  |  |  |  | .8 | .8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B subaenariensis | 8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulimina aculeata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B. exilis | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Cassidulina subglobosa | 6 | 9 | 3 | 9 | 2 | 7 | 4 | 9 | 22 | 13 | 5 | 8 | 6 | 3 | 9 | 6 | 3 | 10 | 7 | 9 | 10 | 6 | 8 | 3 | 8 | 7 | 7 | 5 | 6 | 20 |
| Chilostomella oolina | 2 |  |  |  |  |  |  |  |  | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |
| Cibicides robertsonianus | 2 |  |  |  |  |  |  |  | 3 | 2 |  |  | 6 |  | 4 | 4 | 1 |  |  | 3 | 1 | 2 | 3 | 1 | 3 | 5 | 3 |  | .6 |  |
| Ehrenbergina undulata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |
| Eponides polius | 5 |  |  |  |  | 2 |  |  |  |  |  |  |  | .8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| E pusillus |  |  | 9 |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |  |  | 1 | 1 |  |  |  |  |  |  |
| E. tumidulus |  |  |  |  |  |  |  |  | 3 |  |  | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |
| E umbonatus and variants | 8 | 14 | 18 | 5 | 22 | 22 | 19 | 11 | 10 | 13 | 30 | 16 | 13 | 25 | 6 | 8 | 9 | 14 | 31 | 18 | 25 | 22 | 13 | 24 | 11 | 8 | 21 | 9 | 10 | 10 |
| Gyroidina lamarckiana |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G orbicularis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G soldanii variant | 2 |  |  |  | 6 | 4 |  |  |  |  |  |  |  | 2 | .8 |  | 3 |  |  | 10 |  |  |  |  | 2 | 1 |  |  | .6 | .8 |
| Eggerella bradyi |  | 2 |  | 17 | 6 | 13 |  | 7 | 5 |  | 2 | 3 | 2 | 3 | 6 | 2 | 3 | 3 |  | 2 |  | 8 |  | 1 | 12 | 11 | 3 |  | 2 |  |
| Laticarinina pauperata |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nonion formosum |  |  |  |  |  | 4 | 1 | 2 | 3 |  | 2 |  |  | .8 | .8 | 2 |  |  |  |  | 1 |  |  |  | .8 | 3 | 1 | 3 | .6 |  |
| N pompilioides | 3 | 2 | 9 | 5 |  | 2 |  | 2 | 8 | 4 |  | 3 | 5 | 10 | 2 | 4 | 4 | 7 | 24 | 18 | 4 | 6 | 3 | 5 | 2 | 2 |  |  | 2 | 2 |
| Planulina wuellerstorfi | 15 | 9 | 9 | 13 | 2 | 5 | 12 | 7 |  | 6 |  | 16 | 13 | 8 | 10 | 14 | 12 | 10 | 10 | 3 | 8 | 15 | 14 | 15 | 7 | 13 | 18 | 15 | 7 | 9 |
| Plectina apicularis | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Epistominella exigua | 6 | 20 | 9 | 22 | 31 | 18 | 20 | 20 |  | 28 | 28 | 27 | 2 | 20 | 4 | 9 | 25 | 31 | 14 | 14 | 26 | 18 | 17 | 23 | 6 | 2 | 6 | 18 | 4 | 11 |
| E umbonifera | 19 | 9 | 6 | 5 | 6 | 11 | 23 | 17 | 14 | 4 | 2 | 3 | 20 | 10 | 16 | 14 | 22 | 3 |  | 5 | 5 | 6 | 19 | 7 | 22 | 28 | 19 | 30 | 5 | 14 |
| Pullenia bulloides | 6 | 9 | 12 | 5 | 8 |  | 3 | 11 | 8 | 15 | 12 | .3 | 2 | 6 | 4 | 3 | 9 | 7 | 7 | 9 | 6 | 5 | 8 | 9 | 10 | 8 | 13 | 4 | 2 | 9 |
| P. quinqueloba | 3 |  |  |  |  | 2 |  | 2 | 3 | 2 |  |  | 1 | .8 | .8 | 1 | 1 | 7 | 3 |  |  |  |  |  |  |  |  | 1 |  |  |
| P. sp. | 2 |  |  | 9 |  | 2 |  | 4 | 8 | 2 |  | 3 |  | 2 | 1 | 2 | 3 |  |  |  | 2 | 2 |  | 1 | .8 | 2 | 1 |  | 2 | .8 |
| Pyrgo murrhina | 2 | 5 |  |  | 2 |  |  | 2 |  |  | 2 |  | 1 |  | .8 |  | 3 | 3 | 3 | 5 | 2 |  | 4 | 3 | 2 | 1 | 3 | 4 | 1 | 2 |
| P. oblonga |  | 7 | 3 |  |  | 4 | 1 |  |  |  | 2 | 6 |  |  | .8 |  |  |  |  |  | 1 |  |  | 1 |  |  |  |  |  |  |
| Quinqueloculina venusta |  |  | 6 |  |  |  |  |  |  |  | 2 | 3 |  |  | 1 |  | 1 |  |  |  |  |  | 3 |  |  |  | 1 |  | .6 |  |
| Q cf weaveri |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  | .8 | 2 |  |  |  |  |
| Robulus |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |
| Sigmoilina tenuis |  |  |  |  |  |  |  |  |  | 2 |  |  | 1 |  |  | 2 |  |  |  | 2 |  |  |  |  |  |  |  |  |  | 2 |
| Siphotextularia rolshauseni | 3 | 2 |  |  |  |  |  |  | 5 | 4 |  | 3 |  | .8 | 1 | 2 | 1 |  |  | 2 | 4 | 2 | 5 | 1 | 2 | 1 |  | 4 | .6 | 6 |
| Spiroloculina sp |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Textularia australis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 | 1 | 1 | 4 | 2 | 2 |
| Uvigerina hollicki |  | 5 | 12 | 5 | 4 | 5 | 12 | 7 | 8 | 2 | 5 | 3 | 27 | 7 | 29 | 24 |  |  |  |  |  | 6 |  | 2 | 6 | 4 |  |  | 5 | 13 |
| U hollicki variant |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Valvulineria humilis | 3 | 7 |  | 5 |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  |  |  |  | 8 |  |  |  |  |  | 5 |  |  |  |  |  1 |  |  |  |  | 2 |  |  | 1 |  |  |  |  |  |  |
| V bradyi |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |
| V complanata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |

| SAMPLE | 99 | 103 | 104 | 106 | 110 | 115 | 117 | 118 | 119 | 124 | 129 | 133 | 136 | 140 | 142 | 147 | 150 | 155 | 156 | 157 | 162 | 167 | 169 | 174 | 178 | 183 | 187 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 979.5-980 | 1019.5-1020 | 1029.5-1030 | 1049.5-1050 | 1089.5-1090 | 1139.5-1140 | 1159.5-1160 | 1169.5-1170 | 1179.5-1180 | 1229.5-1230 | 1278.5-1279 | 1319.5-1320 | 1349.5-1350 | 1389.5-1390 | 1409.5-1410 | 1459.5-1460 | 1489.5-1490 | 1539.5-1540 | 1549.5-1550 | 1560.5-1561 | 1609.5-1610 | 1659.5-1660 | 1679.5-1680 | 1729.5-1730 | 1769.5-1770 | 1799.5-1800 | 1839.5-1840 |
| PLANKTONIC POPULATION | 2,550 | 3,100 | 3,150 | 5,250 | 2,950 | 3,200 | 2,350 | 580 | 3,950 | 3,900 | 3,500 | 2,050 | 3,050 | 4,550 | 4,900 | 1,000 | 4,700 | 1,450 | 1,050 | 2,500 | 3,000 | 2,400 | 2,500 | 2,700 | 2,050 | 17,350 | 4,350 |
| Candeina nitida |  |  |  |  |  |  |  |  | .2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Globigerina bulloides | 20 | 17 | 15 | 16 | 15 | 21 | 16 | 3 | 25 | 17 | 24 | 14 | 13 | 21 | 13 | 5 | 22 | 11 | 3 | 18 | 21 | 13 | 6 | 15 | 5 | 27 | 22 |
| G. digitata |  |  |  |  |  |  |  |  |  |  |  |  | .3 |  |  |  |  |  |  |  |  | .3 |  |  |  |  |  |
| G. eggeri | 15 | 11 | 35 | 16 | 21 | 11 | 34 | 49 | 10 | .6 | 15 | 12 | 31 | 20 | 37 | 23 | 6 | 37 | 36 | 20 | 14 | 8 | 38 | 37 | 32 | 18 | 12 |
| G. inflata | 27 | 27 | 23 | 28 | 23 | 21 | 26 | 31 | 32 | 40 | 28 | 24 | 28 | 20 | 27 | 43 | 30 | 30 | 35 | 17 | 28 | 25 | 35 | 23 | 37 | 18 | 18 |
| G. pachyderma | 4 | 2 | 5 | 4 | 4 | .7 | 3 | 2 | .4 | 1 | 1 | 2 | 3 | 2 | 4 | 2 |  | 7 | 3 | 1 | .8 | 1 | 5 | 5 | 1 |  | 2 |
| G. quinqueloba |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Globigerinella aequilateralis | .6 | 1 | .3 | .3 | .3 | 1 | 1 |  | 2 | .4 | .5 | .8 | .8 | 1 | .7 | .3 | .7 |  | 4 | 1 | 1 | 3 |  |  |  | 3 | .7 |
| Globigerinita glutinata | 3 | 1 | .3 | 1 | 1 | 2 |  |  | 1 | .4 | 2 | 2 | .5 | 3 |  |  | 2 |  | .4 | 3 | .3 | 2 |  | 2 | .8 | 1 | 2 |
| Globigerinoides conglobata |  | .3 | .8 | .3 | .5 | .5 | R | 2 | .2 | .4 | .5 | .8 |  |  | .3 |  |  | 2 | 1 |  | R | 1 | .3 | .3 | .8 | R | .4 |
| G. rubra | 12 | 15 | 5 | 12 | 11 | 19 | 6 | 3 | 11 | 8 | 15 | 14 | 6 | 12 | 7 | 8 | 13 | 5 | 5 | 14 | 13 | 20 | 5 | 5 | 5 | 12 | 17 |
| G. sacculifera | .6 | 3 | .8 | 2 | 1 | 1 | .3 | .7 | 2 | .8 | 2 | 4 | 2 | 2 | 1 | .7 | 5 | .6 | 1 | 2 | 1 | 2 | 2 | .6 | 1 | 2 | 3 |
| Globorotalia hirsuta | .6 | 6 | .8 | .6 | 4 | 3 | .2 | .3 | .4 | .1 |  | 3 | .3 | 4 | .3 | 6 | 6 | 1 | 12 | 8 | 7 | 4 | .3 | .6 | 1 |  | 2 |
| G. menardii |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. menardii – tumida group | R | .5 | R | .6 | 1 | .4 | .7 | .3 | .4 | .4 |  | .4 | .3 | .7 | .3 | .3 | 1 |  | .4 | 1 | .6 | 1 | .3 | 1 | .4 | 2 | .8 |
| G. punctulata | 2 | 1 | 4 | 5 | 4 | 4 | 6 | 6 | 4 | 3 | 6 | 5 | 5 | 1 | 4 | .7 | 1 | 2 |  | .6 | .3 | 7 | 1 | 1 | 5 | 8 | 6 |
| G. scitula | 4 | 4 | 2 | 2 | 2 | 6 | 1 | .3 | 1 | 2 | 1 | 2 | 1 | 1 | 1 |  | 7 |  | .4 | 3 | 2 | 3 | .3 | 3 | .4 | 1 | 3 |
| G. truncatulinoides | 10 | 9 | 4 | 9 | 9 | 6 | 2 | 1 | 8 | 9 | 8 | 14 | 7 | 8 | 4 | 9 | 6 | 5 | 5 | .1 | 12 | 8 | 4 | 1 | 9 | 6 | 10 |
| Orbulina universa | 1 | 2 | 5 | 3 | .8 | 2 | 3 | 1 | 2 | 2 | 1 | 2 | 3 | 2 | 1 | 2 | 1 | .6 | .4 | .6 | 1 | 2 | 2 | 5 |  | 1 | 1 |
| Pulleniatina obliquiloculata |  | R |  |  |  | .2 |  |  | .2 |  |  |  |  |  |  |  | R |  |  |  |  |  |  |  | .4 |  | R |
| Sphaeroidinella dehiscens |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| BENTHONIC POPULATION | 90 | 120 | 140 | 85 | 140 | 110 | 70 | 70 | 50 | 220 | 70 | 130 | 150 | 200 | 170 | 100 | 130 | 210 | 225 | 90 | 90 | 30 | 80 | 100 | 90 | 450 | 110 |
| Anomalina sp |  |  |  |  |  |  |  |  |  | R |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |
| Bolivina pseudopunctata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B subaenariensis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulimina aculeata |  |  |  |  | .7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| B. exilis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Cassidulina subglobosa | 11 | 9 | 1 | 8 | 4 | 9 | 8 | 1 | 16 | 7 | 9 | 10 | 4 | 4 | 4 | 4 | 12 | 13 | 3 | 9 | 9 | 3 | 5 | 8 | 3 | 11 | 14 |
| Chilostomella oolina |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Cibicides robertsonianus | 1 | .8 |  | 1 |  |  |  |  |  | 1 |  |  | 3 | 1 |  |  |  | 1 |  |  |  | 3 | 1 |  |  | 2 |  |
| Ehrenbergina undulata |  |  |  | 1 | 1 | 2 |  |  |  |  |  |  |  | 1 | .6 |  |  |  |  |  |  |  |  |  |  |  | 1 |
| Eponides polius |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| E pusillus |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| E. tumidulus |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  | .8 | 1 |  |  | 1 |  | 1 | 1 |  |  |  |
| E umbonatus and variants | 8 | 20 | 7 | 14 | 22 | 32 | 15 | 22 | 15 | 16 | 11 | 8 | 7 | 14 | 14 | 21 | 11 | 21 | 22 | 19 | 16 |  | 11 | 10 | 11 | 12 | 9 |
| Gyroidina lamarckiana |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |
| G orbicularis |  |  |  |  |  |  |  |  |  | .7 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G soldanii variant |  | 2 |  | 2 |  | 1 | 3 |  |  | 1 |  | 3 | 4 |  | .6 |  |  | 1 | 2 | 1 | 4 |  |  | 2 |  | 1 | 6 |
| Eggerella bradyi |  |  | 7 | 2 | .7 | 3 | 6 | 3 | 2 | 2 | 7 | 4 | 4 | 5 | 5 | 1 | 7 |  | 3 | 8 | 6 | 3 | 4 | 7 |  | 5 | 2 |
| Laticarinina pauperata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nonion formosum | 1 | .8 | 2 |  | .7 |  |  |  | 2 | .7 | 3 |  |  | 1 |  | 1 |  |  | .4 | 1 | 1 |  | 1 | 2 |  | 1 |  |
| N pompilioides | 2 | 2 | .7 | 1 |  |  | 1 | 1 |  |  |  | 1 | 1 | 4 | 2 | 5 | .8 |  | 3 | 5 | 1 |  | 2 | 1 | 1 | 2 | 1 |
| Planulina wuellerstorfi | 6 | 13 | 3 | 7 | 6 | 5 | 10 | 4 | 9 | 5 |  | 5 | 9 | 16 | 5 | 10 | 10 | 12 | 11 | 10 | 6 | 7 | 22 | 9 | 4 | 1 | 5 |
| Plectina apicularis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Epistominella exigua | 15 | 4 | 11 | 13 | 19 | 10 | 20 | 21 | 9 | 7 | 6 | 21 | 16 | 14 | 17 | 6 | 7 | 15 | 37 | 7 | 7 | 13 | 14 | 33 | 38 | 12 | 10 |
| E umbonifera | 11 | 26 | 1 | 8 | 15 | 29 | 4 | 3 | 9 | 5 | 13 | 20 | 6 | 22 | 6 | 28 | 35 | 15 | 5 | 12 | 34 | 47 | 6 | 2 | 29 | 3 | 7 |
| Pullenia bulloides | 14 | 5 | 4 | 5 | 6 | 5 | 3 | 4 | 4 | 2 | 9 | 6 | 9 | 3 | 4 | 4 | 5 | 5 | 5 | 8 | 9 | 10 | 4 | 1 | 2 | 7 | 6 |
| P. quinqueloba |  |  |  | 2 |  |  |  |  | 2 |  | 1 |  |  | 1 |  |  |  |  | .4 | 1 |  | 3 | 1 | 2 | 1 | 1 | 1 |
| P. sp. |  |  | 3 | 1 | .7 |  | 1 |  |  | 1 | 1 | 3 |  | 2 | 2 | 3 | 2 | 3 | .4 | 2 | 2 |  | 4 | 4 | 1 | 2 |  |
| Pyrgo murrhina | 3 | 3 | 3 |  | 1 |  |  | 6 |  | .7 | 2 | 3 | 1 | 1 | 1 | 3 | .8 | 1 | 2 | 3 |  |  | 4 | 2 | 2 | 1 | 1 |
| P. oblonga |  |  |  |  | 1 | 1 |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Quinqueloculina venusta |  |  |  |  | 3 | 1 | 1 |  |  |  |  |  | 1 |  |  | 2 |  | 1 |  |  |  | 7 |  |  |  | 3 |  |
| Q cf weaveri |  |  | .7 | 1 | 1 |  |  |  | 2 | .7 |  |  |  |  | 1 | 1 |  |  |  |  |  |  |  |  |  |  | 2 |
| Robulus |  | .8 |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |  |
| Sigmoilina tenuis |  |  | .7 | 1 | .7 | 1 | 3 |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 2 |  |  |  |
| Siphotextularia rolshauseni | 9 | .8 | 2 |  | 1 | 1 | 6 | 3 | 2 |  | 4 | 1 |  | 3 | .6 | 5 | .8 | 5 | 2 | 8 | 1 | 3 | 1 | 3 |  |  | 1 |
| Spiroloculina sp |  |  |  |  | .7 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |
| Textularia australis |  | .8 | 1 | 2 | .7 |  | 1 | 1 | 2 | 4 | 3 | 3 |  | 4 | 1 | 3 | 5 | 2 | 1 | 3 | 2 |  | 4 |  |  | 1 | 4 |
| Uvigerina hollicki | 18 | 11 | 44 | 25 | 15 |  |  | 1 |  | 45 | 28 | 10 | 28 |  | 35 | 3 |  | 1 |  |  | 1 |  | 10 | 12 | 4 | 36 | 29 |
| U hollicki variant |  |  |  |  |  |  | 17 | 28 | 25 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Valvulineria humilis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  |  |  | 2 |  |  |  |  |  |  |  | .7 |  | 2 |  |  |  |  |  |  |  |  | 2 | 1 |  |  | 1 |
| V bradyi |  | .8 |  |  |  |  |  |  |  |  | 1 |  | 3 | 1 | 1 |  |  | 3 | 3 | 1 |  |  |  |  |  |  |  |
| V complanata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

TABLE 30. Occurrences of Foraminifera in selected samples from Core 281 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 281 | DEPTH-4,281 M. | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 2 | 3 | 7 | 8 | 9 | 11 | 13 | 15 | 20 | 21 | 22 | 27 | 28 | 30 | 32 | 34 | 35 |
| CM. FROM TOP OF CORE | 2-2.5 | 9.5-10 | 19.5-20 | 59.5-60 | 69.5-70 | 79.5-80 | 99.5-100 | 119.5-120 | 139.5-140 | 189.5-190 | 199.5-200 | 209.5-210 | 259.5-260 | 268.5-269 | 289.5-290 | 309.5-310 | 329.5-330 | 337-337.5 |
| PLANKTONIC POPULATION | 4,000 | 5,300 | 540 | 2,450 | 2,750 | 3,800 | 800 | 3,000 | 5,250 | 2,400 | 2,000 | 2,750 | 4,650 | 6,500 | 3,200 | 6,000 | 22,150 | 1,050 |
| Globigerina bulloides | 18 | 22 | 11 | 28 | 28 | 33 | 14 | 34 | 28 | 27 | 27 | 1[illegible] | 15 | 22 | 27 | 19 | 23 | 3 |
| G digitata | .2 | | | .3 | .6 | | | .3 | | | .2 | | | .2 | | | .1 | |
| G eggeri | 4 | 15 | 15 | 22 | 17 | 11 | 47 | 9 | 11 | 36 | 35 | 37 | 40 | 9 | 20 | 16 | 15 | 27 |
| G inflata | 20 | 34 | 57 | 27 | 23 | 13 | 32 | 18 | 21 | 13 | 16 | 15 | 20 | 20 | 20 | 33 | 30 | 46 |
| G pachyderma | .6 | .3 | 1 | 1 | .6 | | 1 | .5 | .3 | 6 | 3 | 6 | 8 | 1 | 2 | .5 | 1 | 5 |
| G quinqueloba | | | | | | | .5 | | | | | | | | | | | |
| Globigerinella aequilateralis | 3 | 2 | 1 | 1 | .6 | 2 | .5 | 3 | 2 | | .4 | .6 | | 1 | | 2 | .7 | |
| Globigerinita glutinata | 2 | 3 | | 7 | 4 | 4 | | 4 | 1 | 1 | 1 | .3 | .2 | 4 | 3 | .5 | 1 | .4 |
| Globigerinoides conglobata | .2 | .3 | .4 | | | | | .8 | | | | .6 | 3 | .7 | | .3 | .4 | .8 |
| G rubra | 16 | 15 | 10 | 9 | 17 | 19 | 3 | 12 | 15 | 11 | 6 | 8 | 6 | 18 | 15 | 12 | 14 | 6 |
| G sacculifera | 3 | 3 | 1 | 5 | .6 | .8 | | 2 | .3 | .3 | 1 | 1 | .5 | 3 | .8 | 3 | .6 | 4 |
| Globorotalia hirsuta | 10 | 1 | | | .6 | .4 | 2 | 2 | 4 | 2 | 2 | 4 | 1 | 4 | 1 | .8 | .6 | 6 |
| G menardii | 2 | — | — | — | — | — | — | — | — | — | — | — | — | — | → | | | |
| G menardii-tumida group | | | | | | | | | | | | | | .7 | .8 | .5 | | .4 |
| G punctulata | .2 | R | .4 | .3 | .6 | .8 | | .5 | | | 2 | | | | .3 | 3 | 2 | |
| G scitula | 4 | 1 | | .7 | 3 | 8 | .5 | 5 | 2 | | .2 | .6 | .7 | .5 | 1 | 1 | 1 | |
| G truncatulinoides | 14 | 2 | .7 | 3 | 2 | 7 | | 9 | 15 | 3 | 3 | 6 | 4 | 13 | 7 | 9 | 9 | 5 |
| G tumida | .2 | | | | | | | | | | | | | | | | | |
| Orbulina universa | 2 | .3 | 2 | 2 | .6 | 1 | | .8 | 1 | 1 | 3 | 2 | 3 | 2 | 2 | 1 | .6 | .4 |
| Pulleniatina obliquiloculata | .2 | R | | | | | | R | .3 | | | | | | | | | |
| BENTHONIC POPULATION | 60 | 75 | 10 | 60 | 50 | 40 | 40 | 80 | 100 | 50 | 40 | 50 | 50 | 110 | 90 | 210 | 200 | 100 |
| Anomalina sp | | | | | | | | | | | | | | | | .5 | | |
| Cassidulina subglobosa | 7 | 5 | 33 | 2 | 11 | 8 | 3 | 8 | 7 | 4 | 8 | 4 | 4 | 6 | 13 | 8 | 7 | 2 |
| Chilostomella oolina | | | 8 | | | | | | | | 3 | | | | | | .5 | |
| Cibicides robertsonianus | 2 | | | | 5 | 8 | 3 | | 4 | | | | | | | .5 | 1 | 1 |
| Ehrenbergina undulata | | | | | | | | | | 2 | | | | 1 | | .5 | | |
| Eponides pusillus | | | | | | | 3 | | | | | | | | | | | |
| E. umbonatus and variants | 7 | 9 | 8 | 21 | 15 | | 20 | 13 | 9 | 24 | 23 | 21 | 18 | 7 | 8 | 18 | 13 | 31 |
| Gyroidina orbicularis | 3 | 1 | | | | | | | | 2 | 3 | | | 1 | 2 | 2 | 2 | 3 |
| Eggerella bradyi | 5 | 7 | | 3 | 2 | 5 | 5 | 13 | 6 | 7 | 3 | | 4 | 5 | 5 | 4 | 7 | |
| Nonion barleeanum | | | | | | | | | | | | | | | | | .5 | |
| N. formosum | | 1 | | 2 | | | | 1 | 3 | | | 2 | | 2 | 2 | 1 | 2 | 1 |
| N pompilioides | | 4 | | | | 3 | 3 | 4 | 1 | 4 | | | | 2 | | 1 | .5 | 2 |
| Planulina wuellerstorfi | 12 | 15 | 17 | 3 | 15 | 13 | | 8 | 14 | 7 | 10 | 6 | 26 | 18 | 5 | 8 | 8 | 9 |
| Plectina apicularis | 2 | | | | | | | | | | | | | | | | | |
| Epistominella exigua | 2 | 13 | 25 | 23 | 5 | 33 | 23 | 1 | 11 | 20 | 31 | 23 | 6 | 12 | 11 | 16 | 8 | 13 |
| E umbonifera | 42 | 8 | 8 | 19 | 24 | 20 | 8 | 36 | 24 | 2 | 3 | 17 | 18 | 26 | 23 | 12 | 13 | 19 |
| Pullenia bulloides | 12 | 5 | | 15 | 11 | 5 | 8 | 10 | 5 | 13 | 8 | 17 | 14 | 7 | 14 | 9 | 8 | 5 |
| P. quinqueloba | | | | | | 3 | | 3 | | | | | | 2 | | 1 | | |
| P sp. | | 13 | | 2 | 4 | | 5 | 1 | | 7 | | 2 | 4 | 3 | 1 | 1 | 2 | |
| Pyrgo murrhina | 2 | 1 | | 2 | 2 | | 3 | | | 6 | 8 | | 2 | | | 1 | 3 | |
| P. oblonga | | | | | | | | | 1 | | | 2 | | | | | 1 | |
| Quinqueloculina venusta | | 3 | | 2 | 2 | | | 1 | 2 | | | 2 | | 1 | | | .5 | 3 |
| Q. cf. weaveri | 2 | 3 | | | 2 | | | | | | | | 2 | 1 | | .5 | 1 | |
| Robulus | | | | | | | | | | | | | | | | .5 | | |
| Sigmoilina tenuis | | | | | | | | | | | | | | | 1 | | | |
| Siphotextularia rolshauseni | | | | | 2 | 3 | 8 | 1 | | 2 | 3 | 2 | 2 | 1 | 1 | 1 | .5 | 1 |
| Textularia australis | 2 | | | | | | | | | | | | | 4 | | 1 | 2 | |
| Uvigerina hollicki | | 3 | | 3 | | | 5 | | 11 | | | | | 2 | 13 | 11 | 17 | 9 |
| Valvulineria humilis | 2 | 4 | | 2 | 2 | | | | 1 | | | | | | | | | |
| Virgulina advena | | 3 | | | | | 5 | | | | | | | | | .5 | | |
| V. bradyi | | | | | | | | | | | | | | | | | .5 | 1 |
| V. complanata | | | | 3 | | | | | | | | | | | | | | |

TABLE 31. Occurrences of Foraminifera in selected samples from Core 284 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 284 | DEPTH-4,257 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 5 | 11 | 16 | 20 | 25 | 30 | 31 | 38 | 41 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 | 105 | 109 | 110 | 115 | 120 | 123 | 128 |
| CM. FROM TOP OF CORE | 4-4.5 | 39.5-40 | 99.5-100 | 149.5-150 | 189.5-190 | 239.5-240 | 289.5-290 | 329.5-330 | 371-371.5 | 399.5-400 | 439.5-440 | 489.5-490 | 539.5-540 | 589.5-590 | 639.5-640 | 689.5-690 | 739.5-740 | 789.5-790 | 839.5-840 | 889.5-890 | 939.5-940 | 989.5-990 | 1039.5-1040 | 1079.5-1080 | 1089.5-1090 | 1139.5-1140 | 1189.5-1190 | 1219.5-1220 | 1269.5-1270 |
| PLANKTONIC POPULATION | 6,950 | 8,250 | 5,040 | 9,200 | 625 | 1,600 | 3,600 | 11,300 | 11,200 | 4,800 | 7,550 | 4,100 | 2,450 | 4,700 | 5,700 | 12,200 | 21,700 | 800 | 2,900 | 2,800 | 3,300 | 5,100 | 7,050 | 350 | 1,000 | 800 | 1,900 | 2,000 | 3,200 |
| Candeina nitida | | | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | |
| Globigerina bulloides | 41 | 40 | 37 | 44 | 24 | 16 | 48 | 48 | 44 | 26 | 33 | 28 | 22 | 26 | 34 | 36 | 35 | 20 | 17 | 33 | 26 | 32 | 33 | 4 | 7 | 18 | 21 | 20 | 25 |
| G eggeri | 12 | 15 | 22 | 14 | 24 | 33 | 20 | 15 | 16 | 28 | 22 | 21 | 24 | 13 | 17 | 14 | 22 | 21 | 14 | 6 | 22 | 16 | 11 | 1 | 12 | 4 | 26 | 25 | 27 |
| G hexagona | | | | | | | | | | | | | .3 | | | | | | | | | | | | | | | | |
| G. inflata | 18 | 18 | 15 | 8 | 20 | 34 | 9 | 3 | 8 | 14 | 16 | 25 | 27 | 25 | 19 | 16 | 17 | 7 | 26 | 16 | 14 | 14 | 23 | 12 | 35 | 2 | 18 | 27 | 20 |
| G. pachyderma | 15 | 11 | 10 | 11 | 29 | 3 | 16 | 29 | 20 | 23 | 18 | 9 | 5 | 6 | 13 | 7 | 7 | 48 | 29 | 10 | 19 | 12 | 9 | 82 | 41 | 75 | 28 | 15 | 7 |
| G quinqueloba | 1 | 2 | .6 | 5 | | | | 1 | 5 | | 2 | 3 | | .3 | .6 | 1 | 2 | | | | | .6 | | | | | 2 | | |
| Globigerinella aequilateralis | .7 | .4 | .3 | .7 | | 1 | | | .3 | | | 2 | | .7 | | .8 | .3 | | | | | | .5 | | | | .4 | | |
| Globigerinita glutinata | 1 | 3 | 3 | 4 | .6 | 2 | 2 | | | 2 | 4 | 2 | 4 | | 3 | | 7 | .5 | 6 | 6 | 2 | 4 | 2 | | | | 2 | | 2 |
| Globigerinoides conglobata | .2 | | | | | | | | | .3 | | .4 | | | | | | | | | | | 1 | | | | | | |
| G rubra | 7 | 5 | 7 | 8 | .6 | 7 | 4 | 4 | 3 | 4 | 3 | 3 | 10 | 10 | 6 | 10 | 3 | 3 | 3 | 9 | 8 | 8 | 6 | | 2 | | 2 | 6 | 6 |
| G. sacculifera | 5 | .8 | .3 | .7 | | .2 | .4 | | .6 | .3 | | .4 | 1 | 3 | | .8 | 1 | | .6 | 1 | | 1 | .5 | | | | | .8 | 1 |
| Globorotalia hirsuta | .5 | | 1 | | | | 1 | .6 | 1 | .3 | .8 | 1 | 1 | .7 | | 2 | 1 | | 4 | 1 | 2 | 1 | 3 | | .8 | .5 | | .8 | 5 |
| G. menardii-tumida group | | | | | | .2 | | | | | | | | | | .3 | | | .6 | 3 | | .6 | 1 | | .4 | | | .4 | |
| G punctulata | | | .3 | | | .2 | | | | | | | | .3 | | .3 | | | | 1 | | .6 | 2 | | | | | .4 | |
| G scitula | 1 | 1 | .6 | 4 | | | | | | .3 | .4 | 1 | 2 | 6 | .6 | 3 | 1 | .5 | | 8 | 2 | 4 | 1 | | | | | .4 | 1 |
| G. truncatulinoides | 2 | .4 | 2 | | .6 | .7 | | .3 | 1 | 1 | .4 | 2 | 2 | 3 | 4 | 3 | 2 | .5 | .6 | 4 | 2 | 4 | 6 | | .4 | .5 | | 4 | 6 |
| Orbulina universa | .7 | .8 | | | | 1 | | | 2 | 1 | | .4 | .3 | 1 | 2 | .5 | | | | | 1 | 1 | .5 | | .4 | | 1 | .4 | |
| Pulleniatina obliquiloculata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| BENTHONIC POPULATION | 45 | 80 | 115 | 55 | 20 | 30 | 35 | 80 | 50 | 65 | 70 | 50 | 50 | 30 | 55 | 40 | 90 | 30 | 65 | 60 | 105 | 90 | 65 | 85 | 75 | 11 | 70 | 60 | 120 |
| Anomalina sp. | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | | |
| Bolivina pseudopunctata | 2 | 1 | 24 | 2 | 5 | | | | 2 | | | | | | | | | | | | | | | 2 | 1 | | | | |
| Bulimina translucens | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cassidulina subglobosa | 2 | 7 | 1 | 10 | | 10 | | 4 | | 3 | 7 | 6 | 4 | 20 | 7 | 11 | 9 | 15 | 2 | 2 | 2 | 6 | 1 | 14 | 5 | | 7 | 6 | 2 |
| Chilostomella oolina | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cibicides kullenbergi | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C. robertsonianus | 9 | | | | | | | | 2 | | 1 | 2 | | 3 | 2 | | | | | | 1 | 3 | 1 | | | | | | |
| C. sp. | | | | | | | | | | | | | | | | | | | | | | | 5 | | | | | | |
| Ehrenbergina undulata | | | | | | | 6 | 2 | | | 1 | | 2 | | | | | | | | 1 | | | 1 | | | | | |
| Eponides tumidulus | | | | | | | | | | | | | | | | | | | | | 1 | 2 | | | | | | | |
| E. umbonatus and variants | 5 | 16 | 21 | 18 | 20 | 14 | 6 | 13 | 27 | 11 | 6 | 8 | 35 | 3 | 14 | 8 | 9 | 22 | 16 | 8 | 4 | 9 | 9 | 17 | 7 | 18 | 19 | 21 | 11 |
| Gyroidina lamarckiana | | | | | | | | | | | | | | | | | 1 | | | 2 | | | | | | | | | |
| G. soldanii variant | 2 | 9 | | 9 | | | | 10 | | | | | 2 | | 5 | 5 | 1 | 7 | | 2 | | 1 | | | | 9 | | | |
| Eggerella bradyi | 2 | 1 | 2 | 5 | | 3 | | | | | 4 | 2 | | 7 | | | 6 | 7 | 3 | 2 | 5 | 4 | 1 | 4 | 20 | 9 | | 2 | 2 |
| Nonion formosum | | 1 | | | | | | 4 | 2 | 2 | | | 2 | 3 | | | 1 | | | | 1 | 2 | 1 | | | | 1 | 2 | 2 |
| N. germanicum | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | |
| N. pompilioides | 2 | 5 | | 7 | | | 6 | 6 | 2 | 8 | 3 | 2 | 4 | 3 | | 3 | 1 | 4 | 2 | | | 3 | | 5 | 1 | 18 | | 3 | 2 |
| Planulina wuellerstorfi | 11 | 6 | 3 | 2 | 5 | 24 | 3 | 10 | 6 | 8 | 8 | 8 | 4 | 7 | 3 | 3 | 9 | 4 | 8 | 7 | 13 | 6 | 5 | 7 | 4 | | 6 | 15 | 7 |
| Epistominella exigua | 16 | 5 | 3 | 2 | 15 | | 19 | 28 | 23 | 34 | 12 | 8 | 15 | | 25 | 8 | 2 | 11 | 21 | 16 | 19 | 24 | 25 | 2 | 3 | 27 | 28 | 24 | 47 |
| E. umbonifera | 5 | 10 | 1 | 9 | | 3 | | | 10 | | | 4 | 8 | 27 | 5 | 34 | | 11 | 5 | 39 | 8 | 16 | 40 | | | | 3 | 8 | 8 |
| Pullenia bulloides | 14 | 9 | 1 | 10 | 10 | | 17 | 13 | 10 | 8 | 14 | 4 | 4 | | 21 | 8 | 26 | 4 | 3 | 7 | 12 | 4 | | 5 | 15 | 9 | 1 | 3 | 3 |
| P. quinqueloba | 2 | | 1 | 2 | | 3 | | 1 | 2 | | 3 | | | | 2 | | 1 | 4 | | | 2 | 3 | | | | | | | |
| P. sp. | | 3 | 2 | 4 | | | | 1 | 2 | 2 | 3 | 2 | 6 | | 3 | | 4 | 4 | 3 | | 3 | | 1 | | | | 1 | | |
| Pyrgo murrhina | 2 | 4 | 2 | 4 | | 7 | | 2 | 8 | 2 | 3 | | | 3 | 5 | 3 | 2 | | 3 | 3 | 5 | 1 | 1 | 6 | 24 | | | 3 | 4 |
| P. oblonga | 2 | | 1 | | | | 3 | 1 | | 3 | | | | | | | | | | | | | 1 | 12 | | | | | |
| Quinqueloculina venusta | | | | | 5 | | | | 2 | | 3 | | | 3 | 2 | | | | | | | | 1 | | 1 | | 3 | | |
| Q. cf. weaveri | | | | | | | | | | | | 2 | | | 2 | 5 | | | | | | | 1 | | | | | | |
| Robulus | | | | | | | | | | | | | | 3 | 2 | | | 4 | | | | | | | | | | | |
| Sigmoilina tenuis | 2 | | 2 | 2 | | | | | | | | 2 | | | | | 1 | | | | 1 | | | | | | 1 | | |
| Siphotextularia rolshauseni | | 1 | 3 | 2 | 5 | | | | 2 | 3 | 4 | 17 | 4 | 3 | 2 | | 2 | 4 | 3 | | | 3 | 3 | | | | 3 | | 2 |
| Spiroloculina sp. | | | | | | | | | | | 1 | | | | | | | | | | | | | 5 | | | | | |
| Textularia australis | | | | | | | | | | | | | 2 | | | 11 | | | | 12 | 2 | 9 | | 2 | | | | | |
| Triloculina tricarinata | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | |
| Uvigerina hollicki | 11 | 21 | 14 | 10 | 35 | 34 | | | 2 | 3 | 8 | 31 | 6 | 7 | | | | | 18 | | | 1 | | | 9 | 9 | 9 | 8 | 10 |
| U. hollicki variant | | | | | | | | | | | | | | | | | 18 | | | | | | | 16 | | | | | |
| Virgulina advena | 2 | | 11 | | | | | | | | 1 | | | 7 | | | | | | | | 1 | | | 1 | | 3 | | |
| V bradyi | | | | 2 | | | 36 | 4 | | 14 | 15 | | | | | | 6 | | 14 | | 10 | | | 1 | 7 | | 3 | 5 | |
| V. complanata | | | 10 | | | | | | | | | | | | | | | | | | | | | | | | | | .8 |
| V. sp. | | | | | | | 6 | | | | | | | | | | | | | | | | | | | | | | |

TABLE 32. Occurrences of Foraminifera in selected samples from Core 288 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 288 DEPTH-2,684 M | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 6 | 9 | 14 | 19 | 24 | 29 | 31 | 34 | 38 | 39 | 40 | 44 | 47 | 52 | 57 | 62 | 70 | 96 | 101 | 105 | 110 | 114 | 119 | 121 | 124 | 128 | 131 | 132 | 134 |
| CM. FROM TOP OF CORE | 1-2.5 | 49.5-50 | 79.5-80 | 129.5-130 | 179.5-180 | 229.5-230 | 277.5-278 | 299.5-300 | 329.5-330 | 369.5-370 | 379.5-380 | 389.5-390 | 430.5-431 | 459.5-460 | 509.5-510 | 559.5-560 | 609.5-610 | 689.5-690 | 949.5-950 | 999.5-1000 | 1039.5-1040 | 1089.5-1090 | 1129.5-1130 | 1179.5-1180 | 1199.5-1200 | 1229.5-1230 | 1269.5-1270 | 1299.5-1300 | 1309.5-1310 | 1329.5-1330 |
| PLANKTONIC POPULATION | 12,300 | 6,300 | 8,500 | 2,100 | 6,800 | 7,850 | 9,300 | 5,400 | 9,200 | 5,450 | 5,700 | 6,700 | 4,000 | 10,100 | 8,350 | 6,950 | 5,380 |  | 8,300 | 6,500 | 3,800 | 6,200 | 3,550 | 7,300 | 10,500 | 10,500 | 4,000 | 4,150 | 9,400 | 4,450 |
| Globigerina bulloides | 31 | 49 | 48 | 39 | 47 | 52 | 52 | 46 | 51 | 32 | 36 | 46 | 57 | 34 | 35 | 36 | 37 | 39 | 39 | 23 | 41 | 37 | 34 | 38 | 21 | 57 | 28 | 29 | 33 | 26 |
| G. eggeri | 12 | 7 | 10 | 20 | 12 | 7 | 10 | 15 | 11 | 22 | 17 | 12 | 13 | 23 | 15 | 15 | 13 | 15 | 13 | 9 | 26 | 19 | 20 | 7 | 19 | 10 | 25 | 24 | 14 | 20 |
| G. inflata | 16 | 9 | 16 | 22 | 12 | 6 | 7 | 12 | 9 | 8 | 9 | 10 | 4 | 18 | 13 | 17 | 17 | 7 | 9 | 23 | 12 | 10 | 22 | 19 | 25 | 4 | 13 | 7 | 7 | 16 |
| G. pachyderma | 1 | 5 | 8 | 3 | 8 | 9 | 8 | 5 | 5 | 3 | 6 | 5 | 4 | 3 | 2 | .7 | .4 | 10 | 2 | 2 | 3 | 11 | 1 | 4 | .6 | 7 | 4 |  | 13 | 5 |
| G. quinqueloba | 2 | 5 | 6 | 6 | 5 | 13 | 14 | 12 | 10 | 7 | 10 | 9 | 9 | 2 | 6 | 3 | 3 | 9 | 5 | 2 | .8 | 10 | 3 | 4 | 4 | 11 | 5 | 4 | 5 | 3 |
| Globigerinella aequilateralis | 1 | 1 | .6 |  | .7 |  | .2 |  | 1 | 1 | 1 | 1 |  | .3 | .6 |  | .4 |  | .2 | 1 | .4 | .3 | 1 | 2 |  |  | .6 | .4 |  | .7 |
| Globigerinita glutinata | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 3 | 5 | 4 | 3 | 3 | 3 | 3 | 4 | 2 | 2 | 3 | 2 | 5 | 2 | 3 | 2 | 2 | .6 | 5 | 5 | 1 | 4 |
| Globigerinoides conglobata |  |  |  |  |  |  |  |  |  |  |  |  |  | .3 |  |  |  |  |  | R |  |  |  |  |  |  |  |  |  |  |
| G. rubra | 12 | 12 | 3 | .8 | 4 | 1 | .7 | 2 | 3 | 4 | 5 | 4 | 2 | 5 | 5 | 1 | 5 | 4 | 4 | 16 | 4 | 2 | 3 | 5 | 4 | 4 | .8 | 4 | 3 | 2 |
| G. sacculifera | 1 | .3 | .2 | .4 |  | .6 | .2 |  | R |  | .3 |  | .2 |  | R | R |  |  | .2 | .5 |  | .5 |  | 1 | .3 |  | .2 |  |  | .1 |
| Globorotalia hirsuta | 5 | 4 |  |  |  |  |  | .3 | .5 | R | .6 |  | 1 | .6 | 2 | 1 | 4 | 3 | 4 | 3 | 1 | .3 | .7 |  | .3 | .3 | 1 |  | R | 1 |
| G. menardii-tumida group | R |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  | R | .5 |  | R |  | R |  |  |  |  |  |  |
| G. punctulata | .2 | .5 | .2 |  |  |  |  |  |  | .1 | .1 | R |  |  |  |  |  |  | .2 | 2 |  |  | .2 | 1 |  |  |  |  | R |  |
| G. scitula | 9 | 2 | 4 | 5 | 9 | 7 | 4 | 3 | 4 | 12 | 11 | 11 | 5 | 8 | 11 | 7 | 7 | 8 | 12 | 4 | 4 | 7 | 7 | 9 | 8 | 4 | 10 | 9 | 3 | 15 |
| G. truncatulinoides | 7 | 4 | .4 | .4 |  | 2 | .7 | .3 | .7 | 4 | 1 | .5 | .2 | 1 | 6 | 15 | 10 | 1 | 6 | 11 | .8 | .5 | 5 | 7 | 6 | .6 | 5 | 4 | R | 7 |
| Orbulina universa | .2 | .3 |  |  |  |  | .2 |  | R | .7 | .4 | .7 | .6 | 2 |  | .7 | .6 |  | 2 | 2 | 2 | .3 | 1 | .7 | 3 | 2 | .6 | .8 | 2 | .1 |
| Pulleniatina obliquiloculata |  | R |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| [Sphaeroidina bulloides] |  |  |  |  |  |  |  |  |  | .6 | .3 |  |  |  |  |  |  |  |  |  |  |  |  |  | R | R | .4 |  |  |  |
| BENTHONIC POPULATION | 170 | 70 | 120 | 85 | 210 | 125 | 90 | 145 | 180 | 85 | 105 | 170 | 390 | 420 | 135 | 60 | 75 | 0 | 105 | 60 | 280 | 180 | 125 | 80 | 130 | 110 | 110 | 95 | 185 | 50 |
| Anomalina sp. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |
| Bolivina cf minuta | 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | 1 | 2 |  |  |  |  |  |  |  |  |  |  |
| B. pseudopunctata |  |  |  | 2 | 1 |  |  | 1 |  |  |  |  |  |  |  | 3 | 1 |  |  | 2 | 10 |  |  |  |  |  |  |  |  |  |
| Bulimina aculeata |  |  |  |  |  |  |  |  |  | 1 |  |  | .3 |  |  |  |  |  |  | 8 | 27 |  |  |  |  | 1 |  |  |  |  |
| B. alazanensis |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .5 |  |
| Cassidulina carinata |  |  | .8 | 1 | 4 |  |  |  | .6 |  | 4 | 3 | 37 | 45 | .7 |  | 1 |  | 3 | 3 | 4 | 3 | 18 | 1 | 10 |  |  |  |  |  |
| C. crassa |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 9 |  |  |  |  |  |  |  |  |  |
| C. subglobosa | 6 | 3 | .8 |  |  | 2 | 1 |  | .6 |  | 2 | .6 | .5 | 1 | .7 |  | 1 |  | 2 |  |  | 2 |  | 1 |  | 1 |  |  |  | 2 |
| Chilostomella oolina |  |  |  |  | 6 | 6 | 2 | .7 |  |  |  |  | 2 | 1 |  |  |  |  |  |  | 4 | 1 | 2 |  |  |  |  |  | .5 |  |
| Cibicides kullenbergi | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  | 1 |  | 1 |  |  |  |  | 5 |  | 4 |  |  |  |  |
| C. robertsonianus | 1 | 2 |  |  |  | 2 |  | 1 | 3 | 10 | 8 | 2 | .8 |  | .7 | 3 | 4 |  | 5 |  | .7 |  |  | 8 | .8 |  |  |  |  |  |
| C. sp | 6 |  | 4 | 1 |  | .8 | 3 | 5 | 5 | 10 | 8 | 5 | .3 | 1 | 7 | 3 | 4 |  | 7 | 5 | .4 |  | 4 | 6 | 3 | 2 | 5 | 2 | 5 | 4 |
| Eponides umbonatus and variants | 2 | 3 | 3 | 1 | 1 | 4 | 2 | 2 | 3 | 1 |  | .6 | 3 | 3 | 7 | 7 | 5 |  | 3 | 3 | 1 | 3 | 2 | 8 | 16 | 9 | 16 | 12 | 6 | 21 |
| Globobulimina affinis |  |  | 2 | 10 | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .7 |  |  |  |  |  |  |  |  |  |
| Gyroidina lamarckiana |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .4 |  |  |  |  |  |  |  |  |  |
| G. orbicularis |  | 2 | .8 | 1 |  |  |  |  | .6 | 2 |  | 1 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .5 |  |
| G. soldanii variant | 5 | 6 |  | 5 | 4 | .8 | 5 | 3 | 3 | 2 | 3 | 5 | 5 | 1 | 3 | 3 | 4 |  | 2 |  |  |  |  | 1 | 4 | 5 | 1 | 7 | 4 | 4 |
| Hoglundina elegans | 5 | 25 | 8 | 2 | .5 | .8 | 1 | 5 | .6 |  | 1 | 9 | .3 |  | 1 |  | 5 |  | 1 |  | 2 | 1 |  |  |  | 9 |  | 1 |  |  |
| Eggerella bradyi | 3 |  | 2 |  |  | 2 | 1 |  | .6 | 4 | 1 | 2 | .5 | 1 | 1 |  | 4 |  | 2 | 5 | .7 |  |  | 4 | 2 | 6 | 1 | 1 | .5 | 2 |
| Laticarinina pauperata | 5 | 4 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  | 3 |  |  |  | 1 | .8 | 1 |  |  |  |  |
| Nonion barleeanum | 1 |  | 20 | 23 | 16 | 9 | 5 | 5 | 8 | 2 | 8 | 6 | 5 | 8 | 7 | 5 | 4 |  | 5 | 2 | 5 | 4 | 7 | 6 | 5 | 4 |  | 1 | 13 | 4 |
| N. formosum |  | 2 | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| N. germanicum | 1 |  | 7 | 21 | 21 | 7 | 2 | 1 | 2 | 2 | 1 | .6 | 2 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| N. pompilioides | 1 | 2 | 5 | 1 | 2 | 3 | 10 | 3 | 5 | 7 | 8 |  |  | 2 | 8 | 13 | 9 |  | 1 | 8 | 2 | 6 |  | 6 | 6 | 26 | 8 | 7 | 12 | 13 |
| Planulina wuellerstorfi | 16 | 4 | 11 |  | 2 | 4 | 6 | 8 | 6 | 13 | 5 | 10 | 2 | 3 | 19 | 18 | 15 |  | 23 | 34 | 2 |  | 3 | 15 | 19 | 22 | 9 | 12 | 10 | 23 |
| Epistominella exigua | 12 | 15 | 13 | 10 | 18 | 26 | 24 | 12 | 18 | 14 | 9 | 24 | 4 | 2 | 15 | 25 | 21 |  | 7 | 11 | .7 | 1 | 14 | 16 | 4 |  |  |  | 8 |  |
| E. umbonifera | 3 | 4 | 3 |  |  |  | 1 | 1 | 7 | 4 | 1 |  | .3 | 5 | 5 |  |  |  |  |  |  |  |  |  |  | 6 | 9 |  | 1 |  |
| Pullenia bulloides | 7 | 6 | 3 | 2 | 3 | 2 |  | .7 | .6 |  |  | 1 | 2 | 1 | 1 | 2 | 3 |  | 3 | 2 | 3 | 2 | 7 | 3 | 5 | 4 | 6 | 5 | 2 | 2 |
| P. quinqueloba |  | 3 | .8 | 1 | 4 | 5 | 5 | .7 | 2 | 2 | 1 | 1 | 1 | .5 | .7 |  |  |  | 2 | 2 | .4 | 3 | 2 | 10 | 2 | 2 | 1 |  |  | 4 |
| P. sp | 1 | 2 | .8 |  |  | 2 | 1 | 3 | 2 | 1 | 3 | .6 | .5 | 2 | 3 |  | 1 |  |  | 2 | 3 | 1 | .8 | 3 | .8 |  | 1 |  | .5 |  |
| Pyrgo murrhina |  | 2 |  |  | 1 |  | 1 | 1 | 3 | 6 | 6 | 1 | .5 |  | 1 |  |  |  | 3 |  |  | 1 | 2 |  |  |  |  | 6 | .5 |  |
| P. oblonga |  |  |  |  | 2 |  |  |  |  |  |  |  | .5 |  |  |  |  |  |  |  | 2 | 1 | 4 |  |  |  |  |  | 3 |  |
| Quinqueloculina venusta | 5 |  |  |  |  | .8 |  | .7 |  |  | 1 |  |  |  |  |  |  |  | 2 |  |  |  |  |  | 2 |  |  |  | 1 | 2 |
| Q. cf. weaveri | 1 |  |  |  |  |  |  | .7 | 1 | 2 | 2 | .6 |  |  | 1 |  |  |  |  |  | .4 |  |  |  |  | 2 |  | 2 |  |  |
| Robertina bradyi | 2 | 1 |  |  |  |  |  |  |  | 2 | 3 | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |
| Robulus |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  | 1 |  | .4 |  |  |  |  |  | 1 | 2 |  |  |
| Sigmoilina schlumbergeri | 5 |  | 2 |  | 1 | 2 | 3 |  | .6 |  | 2 | 4 |  |  | 2 | 3 | 4 |  |  | 2 | 1 | 1 | .8 | 4 | 3 | 2 | 1 |  | 1 |  |
| Siphotextularia curta |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| S. rolshauseni | 3 | 2 | 2 |  |  | 2 | 3 | 1 | 2 | 4 | 6 | 1 | .3 | 1 |  | 5 |  |  | 3 | 3 | .4 |  |  | 1 | 2 | 1 |  | 2 |  | 2 |
| Spiroloculina sp. |  |  | .8 |  |  |  |  | .7 |  |  |  |  |  |  |  |  | 1 |  |  |  | .4 |  |  |  | .8 |  |  | 1 |  |  |
| Spirophthalmidium acutimargo |  |  | 2 |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Triloculina tricarinata |  |  |  |  |  | 5 | 9 | 5 | 9 | 5 | 5 | 3 | 3 | 6 | 2 |  |  |  | 1 |  | 3 | 7 | 3 | 1 | 8 |  | 3 | 7 | 2 |  |
| Uvigerina auberiana and variant | 2 |  | .8 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| U. hollicki |  |  | .8 | 11 | 2 |  | 8 | 36 | 14 | 5 | 15 | 12 | 24 | 13 |  |  | 5 |  | 20 | 2 | 13 | 59 | 25 |  | .8 |  | 33 | 21 | 29 | 9 |
| Valvulineria humilis |  | 10 |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  |  | .8 | 1 | 1 | 3 |  |  | 1 |  |  |  | .3 | 1 | 5 | 5 |  |  |  | 2 | .4 | 1 | 4 |  | 2 |  | 1 | 5 | .5 | 4 |
| V. bradyi |  | 2 | 2 | 6 | 7 | 10 | 3 | 1 | 3 | 1 |  | 2 | 4 | 3 | 4 | 3 | 1 |  | 1 |  |  |  | .8 |  | 7 | 2 | 6 | 1 | 4 | 2 |
| V. complanata |  |  | .8 |  |  | 2 |  |  |  |  |  |  |  | 1 |  |  |  |  | 1 |  | .7 | 1 |  |  |  |  |  |  |  |  |

**Core 281.** This core has four shifts to a cooler-than modern fauna at 337 cm., separated by modern assemblages. *Globorotalia tumida* is only in the upper sample.

**Core 284.** This core contains a high percentage of *Globigerina pachyderma* in all samples except in the lowermost section, and the frequencies of *Globorotalia truncatulinoides* are uniformly low. The top sample at 4—4.5 cm. contains a fauna which has a higher frequency of *Globigerina pachyderma* and a lower frequency of *Globorotalia truncatulinoides* and *G. menardii* than the surface sample taken from the same station. *G. tumida* occurs only in the surface sample taken with the small coring device.

TABLE 33. Occurrences of Foraminifera in selected samples from Core 289 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 289 | DEPTH - 2640 M. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1A | 5 | 9 | 14 | 19 | 24 | 28 | 33 | 38 | 41 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 79 | 84 | 89 | 94 | 99 | 101 | 103 | 108 | 109 | 110 | 112 | 113 | 118 | 119 | 124 |
| CM. FROM TOP OF CORE | 0.5-1 | 39.5-40 | 79.5-80 | 129.5-130 | 179.5-180 | 229.5-230 | 269.5-270 | 319.5-320 | 369.5-370 | 399.5-400 | 439.5-440 | 489.5-490 | 539.5-540 | 589.5-590 | 639.5-640 | 689.5-690 | 739.5-740 | 779.5-780 | 829.5-830 | 879.5-880 | 929.5-930 | 979.5-980 | 999.5-1000 | 1019.5-1020 | 1069.5-1070 | 1079.5-1080 | 1089.5-1090 | 1109.5-1110 | 1119.5-1120 | 1169.5-1170 | 1179.5-1180 | 1229.5-1230 |
| PLANKTONIC POPULATION | 10,000 | 8,400 | 7,000 | 13,000 | 7,750 | 3,500 | 6,100 | 4,800 | 6,400 | 7,000 | 6,600 | 11,300 | 3,600 | 4,500 | 6,050 | 10,800 | 9,600 | 26,400 | 12,000 | 7,600 | 5,100 | 8,800 | 8,100 | 11,300 | 8,100 | 7,300 | 6,200 | 9,700 | 2,000 | 2,600 | 4,200 | 4,560 |
| Globigerina altispira | | | | | | | | | | | | | | | | | | | | | | .4 | | | | | | | | | | |
| G. bulloides | 44 | 43 | 48 | 40 | 60 | 45 | 53 | 28 | 42 | 24 | 36 | 42 | 32 | 40 | 21 | 53 | 42 | 50 | 28 | 29 | 34 | 47 | 26 | 34 | 37 | 29 | 18 | 35 | 27 | 39 | 39 | 45 |
| G digitata | | | | | | | R | | | | | | | | | | | | | | | | | | | | | | | | | |
| G. eggeri | 9 | 11 | 13 | 22 | 7 | 16 | 12 | 21 | 14 | 33 | 18 | 17 | 22 | 17 | 22 | 13 | 26 | 12 | 25 | 31 | 15 | 11 | 17 | 8 | 24 | 26 | 31 | 29 | 25 | 14 | 16 | 23 |
| G. inflata | 18 | 10 | 10 | 16 | 4 | 11 | 9 | 8 | 6 | 14 | 14 | 6 | 11 | 15 | 28 | 7 | 14 | 4 | 15 | 15 | 16 | 16 | 25 | 14 | 11 | 8 | 14 | 7 | 18 | 17 | 11 | 11 |
| G pachyderma | .6 | 3 | 6 | 4 | 10 | 7 | 6 | 3 | 11 | 3 | 3 | 2 | 1 | 2 | | 3 | 3 | 9 | 3 | 3 | 1 | 5 | .8 | 2 | 4 | 7 | 7 | 8 | 2 | 4 | 4 | 1 |
| G. quinqueloba | 1 | 4 | 11 | 4 | 6 | 7 | 9 | 19 | 13 | 11 | 6 | 8 | 8 | 6 | 2 | 7 | 5 | 17 | 12 | 12 | 4 | 5 | 7 | 12 | 8 | 12 | 15 | 7 | 4 | 3 | 12 | 4 |
| Globigerinella aequilateralis | 2 | 1 | | .5 | | | | .7 | | | 1 | .3 | | | R | 1 | | | | | | .7 | | 1 | | | | | | | | |
| Globigerinita glutinata | 1 | 2 | 2 | 3 | 2 | 5 | 2 | 5 | 3 | 2 | 2 | .8 | 1 | 1 | 3 | 2 | 2 | | 2 | .4 | 3 | 2 | 3 | 2 | 5 | 3 | 2 | 1 | 8 | 3 | .8 | 1 |
| Globigerinoides conglobata | R | | | R | | | | | | R | | .3 | R | | | R | | | | | | .4 | | R | | | | | | | | |
| G rubra | 3 | 11 | 4 | 2 | .8 | 1 | 3 | 3 | .5 | 3 | 6 | 5 | 4 | 6 | 6 | 6 | 3 | 2 | 2 | 1 | 11 | 2 | 4 | 10 | 2 | 2 | 3 | 3 | .6 | 2 | 2 | 2 |
| G sacculifera | 2 | .4 | | | R | | | | | | | .6 | | | 1 | | R | | | | | 1 | | .3 | .4 | | | | | | | |
| Globorotalia hirsuta | 6 | 6 | .5 | | R | | 1 | R | R | .8 | 3 | 1 | 3 | R | 2 | R | 1 | .7 | 5 | .8 | 1 | .4 | 1 | 4 | 1 | .4 | | .2 | .6 | .6 | .8 | .7 |
| G menardii-tumida group | R | R | | | | | | | | | | | | R | R | | | | | | | | | R | | | R | | | | | |
| G punctulata | R | | | | | | | | | | | | | .7 | | .3 | | | | | | .7 | | | | 1 | R | .2 | | .6 | 2 | R |
| G scitula | 8 | 3 | 5 | 8 | 9 | 7 | 5 | 10 | 9 | 7 | 10 | 8 | 7 | 6 | 6 | 2 | 2 | 5 | 9 | 4 | 8 | 6 | 7 | 6 | 4 | 10 | 9 | 7 | 9 | 15 | 10 | 5 |
| G. truncatulinoides | 4 | 5 | 1 | R | R | .5 | R | 2 | .5 | .8 | 3 | 8 | 10 | 5 | 9 | 3 | R | R | 1 | 3 | 6 | 1 | 8 | 5 | 4 | 1 | .8 | .2 | 7 | 2 | .8 | 5 |
| Orbulina universa | .6 | | | R | .8 | | .5 | | 2 | 1 | .4 | 1 | | | .5 | 1 | 2 | .7 | 2 | .8 | 1 | 2 | .8 | 1 | .4 | | | 1 | | .6 | 1 | 3 |
| Pulleniatina obliquiloculata | | | | | | | | | | | | | | | R | | | | | | | | | | | | | | | | | |
| [Sphaeroidina bulloides] | | | | | | R | R | | | | | | | | | | | | | | | | .4 | | R | R | R | | | | | |
| BENTHONIC POPULATION | 105 | 80 | 110 | 250 | 100 | 50 | 105 | 90 | 160 | 600 | 110 | 140 | 30 | 50 | 80 | 125 | 300 | 150 | 400 | 60 | 50 | 90 | 125 | 100 | 70 | 110 | 60 | 170 | 210 | 60 | 130 | 30 |
| Anomalina sp | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | 3 |
| Bolivina cf. minuta | | 3 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | 1 | | | | |
| B pseudopunctata | | | | | 2 | | 1 | | | | | 1 | | | 2 | 2 | 4 | | | | | | | | | | | | | | | |
| Bulimina aculeata | | | | | | | | | | .3 | | | | | | 13 | 28 | 6 | .5 | | | | | | | | | | | | 2 | |
| B. alazanensis | | | 1 | | | | | | | | | | | | | 2 | | | | 2 | | | | | | | 2 | | | | | 3 |
| Cassidulina carinata | | | | | | | | 1 | 36 | 51 | 2 | | | 2 | 12 | 13 | 3 | 3 | 10 | 17 | | 2 | 25 | | | | 2 | | | | | |
| C. subglobosa | | 3 | 1 | | | 2 | | | | | | | | | | | 6 | 3 | .5 | | | | 2 | 4 | 1 | 3 | 2 | | | | | 3 |
| Chilostomella oolina | | | | 5 | 4 | 2 | 3 | | | | | 1 | | | | | 3 | | .5 | 3 | | | 2 | | | | | 2 | | | | |
| Cibicides kullenbergi | | 5 | | | | | | | | | | | | | 2 | | | | | | | | | 6 | | | | | | 2 | | |
| C robertsonianus | 2 | 3 | 2 | 2 | 4 | 4 | 4 | 3 | | 3 | | 3 | | 2 | 2 | 2 | | 1 | .5 | | | 2 | | 4 | | 3 | | 1 | | 5 | 2 | |
| C. sp | 4 | 3 | 4 | | 3 | 4 | 6 | 13 | | | 11 | 4 | 7 | 2 | | 6 | | 4 | 3 | 3 | 10 | 6 | 6 | | 5 | 7 | 3 | 2 | 2 | 3 | 2 | 3 |
| Eponides umbonatus and variants | 4 | | 4 | | 2 | 6 | | 5 | 2 | 1 | 4 | 7 | | 2 | 7 | | 2 | 6 | 2 | | 2 | 7 | 16 | 15 | 16 | 16 | 12 | 1 | 6 | 28 | 28 | 19 |
| Gyroidina lamarckiana | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| G. soldanii variant | 2 | | 3 | | 2 | 8 | 2 | 5 | 7 | 3 | 2 | 3 | | 9 | 2 | 3 | | 1 | | 2 | | 11 | 6 | 2 | 5 | 2 | 7 | 1 | 2 | 10 | 7 | 3 |
| Höglundina elegans | 9 | 13 | 14 | | 4 | | | 4 | 5 | 2 | | | 4 | | 5 | | .7 | 1 | | 3 | | | | 6 | 3 | 2 | 2 | | 1 | | | |
| Eggerella bradyi | 6 | 3 | 1 | | 4 | | 2 | 3 | | .3 | | 4 | | | 5 | 2 | 3 | 1 | | 2 | 4 | 2 | 5 | | | 2 | | | | 3 | | |
| Laticarinina pauperata | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Nonion barleeanum | 8 | 5 | 17 | 23 | | 2 | 4 | 3 | 6 | 4 | 4 | 10 | 7 | 7 | | 5 | 9 | 4 | 4 | 3 | | 6 | 10 | | 3 | 3 | 10 | 8 | 9 | 2 | 6 | |
| N. germanicum | | | 2 | 13 | 2 | | 2 | | | 1 | | | | | | | | | .5 | | | | | | | | | | | | | |
| N pompilioides | 12 | 10 | 7 | 8 | 2 | 4 | 5 | 4 | 1 | | | 7 | 11 | 7 | 10 | 11 | 3 | 8 | 1 | 2 | | 15 | 13 | 10 | 11 | 14 | 7 | 2 | 12 | 8 | 11 | 16 |
| Ophthalmidium inconstans | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 12 | 5 | 7 | 6 | 8 | 4 | 5 | 9 | 5 | 1 | 31 | 16 | 21 | 19 | 12 | 19 | 2 | 7 | 3 | | 8 | 15 | 6 | 27 | 12 | 9 | 17 | 6 | 6 | 18 | 9 | 13 |
| Epistominella exigua | 19 | 3 | 12 | 10 | 20 | 26 | 23 | 4 | 4 | .3 | 13 | 22 | 36 | 6 | 7 | 13 | 2 | 13 | 6 | 3 | 14 | 10 | 3 | | | | | 5 | 1 | 5 | 3 | |
| E. umbonifera | | | 3 | | 2 | 2 | 7 | 2 | 1 | | 4 | | | | | | | | | | | | | 4 | 3 | 3 | 2 | | | | | |
| Pullenia bulloides | 6 | 3 | 3 | | 2 | 4 | 2 | | 2 | 2 | | 3 | 4 | 6 | 2 | 5 | 7 | 3 | 5 | 10 | 4 | 1 | | 6 | 3 | 9 | 9 | 2 | | | 2 | 3 |
| P quinqueloba | | 5 | 3 | | 6 | 2 | 1 | 2 | 1 | .3 | 2 | | 4 | | 5 | | .7 | | .5 | 3 | | 3 | 2 | 2 | 4 | 3 | | .4 | | 2 | | 3 |
| P. sp. | | 5 | 3 | 2 | | 2 | 4 | | 4 | 2 | | | | 2 | | | 2 | 1 | | 2 | | 1 | | | 3 | | | 2 | | | | 3 |
| Pyrgo murrhina | | | | 3 | | | | 5 | | .3 | 9 | | | 2 | 5 | 2 | | 6 | 1 | | 2 | 1 | | 2 | | 4 | 3 | | | | | |
| P oblonga | | | 1 | 3 | 4 | 2 | 1 | | 2 | 1 | | | | 2 | | 3 | 3 | 1 | 3 | 8 | | 1 | | | 1 | | | | 2 | | | |
| Quinqueloculina venusta | 4 | 8 | | 2 | | | | 1 | | .3 | | | | 2 | 2 | | | | .5 | | 4 | 5 | | | | | | | | | | |
| Q cf weaveri | 4 | 5 | | | 2 | | 3 | 4 | | | | | | | 2 | | .7 | 3 | | | 2 | | | | | 3 | | | 1 | | | |
| Robulus | | | 1 | | | | | | | | | | | | | | .7 | | | | | | | 2 | | | | | | | | |
| Sigmoilina schlumbergeri | 2 | | 2 | | | | | 8 | 1 | | 2 | 9 | | | 2 | 2 | 2 | | 4 | | | | 2 | 6 | 4 | 7 | 5 | | | 5 | 2 | 9 |
| Siphotextularia rolshauseni | | 3 | | 2 | | | 3 | 7 | | .3 | | | | | | | 2 | 1 | 1 | 3 | | | 2 | 4 | | | 2 | | | | 2 | |
| Spiroloculina sp | | | | | 2 | | 3 | | | | | 1 | | | 2 | | | | | | | | | | | | | | | | | |
| Triloculina tricarinata | 4 | 5 | 2 | | 2 | 4 | 8 | 5 | 1 | 17 | 2 | 3 | 4 | 2 | 2 | | 4 | 6 | 5 | 3 | | 7 | 2 | 2 | 1 | 3 | 9 | 2 | 6 | 2 | 3 | |
| Uvigerina hollicki | | | 2 | 10 | | 14 | 9 | 5 | 19 | 7 | | | 4 | 22 | 5 | | 12 | 21 | 43 | 30 | 50 | | | | 21 | 2 | 5 | 41 | 52 | | 6 | 3 |
| Valvulinerio humilis | 2 | 8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina advena | | 3 | 3 | | 4 | 2 | 2 | | | .3 | 4 | 1 | | 7 | 5 | | .7 | | 6 | 2 | | 2 | | | 1 | 2 | | 11 | 2 | | 6 | 13 |
| V. bradyi | 2 | | | 14 | 12 | 6 | 2 | 1 | 1 | 4 | 11 | 1 | | | | | .7 | | 1 | | | 1 | | | 1 | | | 6 | | 7 | 11 | |
| V complanata | | | | | 2 | | | 1 | | .7 | 2 | | | | | | | | | | | | | | | | 2 | | | | | 3 |

**Core 288.** The top sample of the core is the modern assemblage. The faunas indicate six shifts to cooler surface water conditions than present ones at this location.

**Core 289.** The top sample contains the modern fauna and there appear to be five shifts to a somewhat higher-latitude assemblage separated by the modern mid-latitude fauna.

**Core 290.** Vertical faunal variations are relatively small, and may have little or no significance in this core. There appear to be three changes in faunal composition which are tentatively interpreted as shifts to slightly cooler conditions.

**Core 292** contains six faunas which seem to represent somewhat higher latitude condi-

ABLE 34. Occurrences of Foraminifera in selected amples from Core 290 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 290 | DEPTH-1,995 M. | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AMPLE | 1A | 4 | 9 | 14 | 16 | 21 | 26 | 31 | 33 | 35 | 40 | 42 | 47 | 52 | 54 | 59 | 60 | 64 |
| M. FROM TOP OF CORE | 0-15 | 49.5-50 | 97.5-98 | 149.5-150 | 168.5-169 | 219.5-220 | 269.5-270 | 319.5-320 | 339.5-340 | 369.5-370 | 409.5-410 | 429.5-430 | 479.5-480 | 529.5-530 | 549.5-550 | 599.5-600 | 609.5-610 | 649.5-650 |
| LANKTONIC POPULATION | 20,100 | 29,500 | 14,000 | 44,800 | 26,100 | 26,800 | 37,900 | 36,700 | 16,300 | 12,000 | 22,400 | 11,900 | 11,700 | 19,200 | 8,600 | 26,200 | 11,100 | 21,700 |
| obigerina bulloides | 47 | 42 | 35 | 58 | 44 | 36 | 47 | 46 | 49 | 46 | 48 | 46 | 50 | 42 | 35 | 41 | 40 | 31 |
| eggeri | 9 | 11 | 12 | 16 | 9 | 13 | 15 | 15 | 18 | 16 | 18 | 18 | 15 | 22 | 14 | 19 | 21 | 14 |
| inflata | 15 | 21 | 20 | 11 | 19 | 20 | 16 | 16 | 9 | 11 | 11 | 8 | 11 | 15 | 13 | 14 | 14 | 14 |
| pachyderma | 2 | 2 | 1 | 2 | 4 | 1 | 3 | 2 | 3 | 3 | 3 | 4 | 3 | .8 | 4 | 3 | 2 | 3 |
| quinqueloba | .6 | 4 | 5 | 4 | 5 | 2 | 2 | 3 | 2 | 1 | 2 | 3 | 5 | 4 | 7 | 5 | 2 | 17 |
| lobigerinella aequilateralis | 1 | 7 | .7 | | 1 | 1 | .5 | 1 | .2 | .3 | | .3 | | .2 | .4 | .2 | .9 | .7 |
| lobigerinita glutinata | 1 | 2 | 2 | 1 | 3 | 3 | .4 | 2 | 4 | 5 | 4 | 3 | 3 | 2 | 4 | 2 | 1 | 3 |
| lobigerinoides conglobata | | | | | .2 | R | | | | | | .1 | | | | | | |
| rubra | 6 | 5 | 6 | 3 | 4 | 6 | 2 | 3 | 2 | 3 | 3 | 1 | 2 | 3 | 6 | 4 | 3 | 4 |
| sacculifera | .5 | | .5 | | | .2 | .2 | 1 | 1 | | | | | | | | | .3 |
| loborotalia hirsuta | 4 | 1 | 1 | .2 | 1 | .7 | R | 1 | | .3 | 1 | .5 | 1 | 1 | 1 | .5 | 1 | 1 |
| menardii | R | | | | | | | | | | | | | | | | | |
| menardii – tumida group | | R | | | | | R | | | | | | R | | | | | R |
| punctulata | 2 | | | | R | | .2 | | | .5 | | | | | 1 | .2 | | |
| scitula | 8 | 4 | 7 | 4 | 5 | 10 | 6 | 5 | 10 | 12 | 9 | 12 | 6 | 5 | 5 | 9 | 9 | 8 |
| truncatulinoides | 5 | 6 | 9 | .6 | 5 | 5 | 5 | 4 | 2 | 2 | 2 | 2 | 2 | 4 | 8 | .7 | 3 | 4 |
| rbulina universa | 5 | 7 | .2 | .9 | 2 | 2 | 2 | .7 | .8 | | .6 | 2 | 1 | .3 | 1 | 1 | 2 | 2 |
| phaeroidina bulloides] | | R | .2 | | | | | | | | | | | | | | | |
| ENTHONIC POPULATION | 160 | 400 | 200 | 350 | 230 | 370 | 170 | 600 | 190 | 375 | 1,000 | 225 | 250 | 360 | 190 | 1,000 | 1650 | 295 |
| olivina cf minuta | 2 | 5 | 6 | .6 | 3 | 2 | 4 | 5 | 6 | 16 | 11 | 4 | 3 | 5 | 9 | .8 | 5 | |
| pseudopunctata | .6 | 2 | | | 3 | .5 | | | 4 | 3 | 3 | 2 | .8 | | 2 | .8 | .7 | |
| pusilla | | | | | | | | | | | | | | | 1 | .8 | | 5 |
| ulimina aculeata | .6 | 2 | 5 | 3 | 2 | .5 | 9 | 23 | 37 | 42 | 57 | 25 | 49 | 66 | 15 | 9 | | .7 |
| alozanensis | 1 | .5 | | .6 | 2 | 1 | 4 | 7 | 1 | 1 | 1 | 1 | | | 2 | | .5 | |
| mexicana | | | | | | | | 1 | 2 | 5 | 5 | | 1 | 2 | | | 1 | |
| assidulina carinata | 2 | 11 | 17 | 33 | 12 | 14 | 8 | 1 | 2 | 4 | .2 | | | .8 | 8 | 29 | 56 | 11 |
| crassa | .6 | | | | | | | | | | | | | | | | | |
| subglobosa | 5 | 9 | 8 | 7 | 9 | 14 | 14 | 8 | 8 | 8 | 6 | 17 | 10 | 3 | 15 | 5 | 9 | 14 |
| ibicides kullenbergi | 14 | 1 | 4 | 2 | 6 | 3 | 6 | 7 | 1 | .5 | .6 | 3 | 1 | | | .8 | .2 | |
| robertsonianus | | .5 | | | | | | | | | | | | | | | | .7 |
| sp | .6 | .5 | 2 | .6 | 1 | .5 | | | | | .2 | 1 | .8 | .3 | .5 | 2 | 1 | .7 |
| iscorbis williamsoni | .6 | .5 | 1 | .6 | | .5 | .6 | | 2 | 1 | .4 | 2 | 3 | | | .4 | .7 | .7 |
| hrenbergina undulata | | | | 1 | 3 | 5 | 2 | 4 | 1 | 2 | .2 | 3 | 3 | 2 | 3 | 2 | .7 | 3 |
| ponides umbonatus and variants | | 1 | 1 | 2 | 2 | 1 | 4 | 1 | 4 | 3 | 4 | 5 | 2 | .3 | 1 | 2 | 3 | 1 |
| yroidina orbicularis | 7 | 7 | 5 | 4 | 3 | 3 | 2 | 4 | | 2 | 1 | | .8 | | .5 | .4 | | |
| soldanii variant | 4 | | | .6 | 3 | 1 | 4 | 3 | 3 | 2 | 1 | 2 | | .3 | .5 | 2 | 2 | 7 |
| öglundina elegans | 10 | .5 | | .6 | | | | | | | | | | | | | | |
| ggerella bradyi | 3 | 3 | 3 | 3 | | 1 | 2 | 4 | 3 | 3 | .6 | 3 | 2 | 2 | 3 | 3 | 1 | 7 |
| aticarinina pauperata | 2 | .5 | | | | 1 | .6 | | | .5 | | 2 | 1 | .3 | 2 | | .5 | 2 |
| onion barleeanum | .6 | 3 | | 1 | | | | 1 | | | | | | | | | | |
| formosum | | | | | | | 1 | | | | .2 | | | | .5 | | | |
| pompilioides | 4 | 5 | | 8 | 5 | 3 | 4 | 2 | 5 | 1 | 1 | 5 | .8 | 2 | 6 | 4 | 3 | 4 |
| lanulina ariminensis | | 2 | 2 | | | .5 | .6 | .7 | | | .2 | | .8 | | .5 | .4 | | |
| wuellerstorfi | 20 | 16 | 11 | 7 | 6 | 6 | 9 | 11 | 2 | 2 | 2 | 2 | 10 | 3 | 8 | 5 | 2 | 6 |
| pistominella exigua | 2 | 11 | 16 | 6 | 17 | 20 | 13 | .7 | 2 | 1 | .6 | | .8 | .3 | 5 | 15 | 7 | 9 |
| umbonifera | | | | | | | | | | | | | | | | | | 1 |
| ullenia bulloides | 1 | 2 | | 6 | 2 | 9 | 4 | 3 | 1 | 1 | 1 | 4 | .8 | .3 | 4 | .4 | .7 | |
| quinqueloba | 2 | 3 | 1 | 2 | 3 | 2 | 4 | 2 | 1 | 1 | .4 | 5 | .8 | | .5 | | .2 | .7 |
| sp | | | | .6 | | | 1 | .7 | 1 | 1 | 1 | | | .3 | | 1 | | |
| yrgo murrhina | | | | | | | | | | | | 1 | | | | | | |
| otamorphina laevigata | | | | | | | 1 | .7 | | | .6 | | | | | | | |
| cf. weaveri | 2 | .5 | | | | | | | | | | | | | | | | 1 |
| obulus | 1 | 1 | | | 1 | .5 | | .7 | | | .4 | | | | | | | |
| Rotalia" praegeri | 2 | 3 | 9 | | 4 | 2 | 1 | | | | .2 | 3 | .8 | 2 | | | | |
| upertia stabilis | .6 | .5 | | | | | | | | | | | | | .5 | | | 2 |
| igmoilina schlumbergeri | 4 | 1 | | 6 | 5 | 4 | | | 4 | 2 | .2 | 1 | | 1 | 3 | | | |
| tenuis | | | | | | | | | | | | | | .3 | .5 | | | .7 |
| iphotextularia curta | 2 | 2 | 1 | .6 | 1 | | .6 | .7 | 1 | .5 | .2 | 3 | 3 | .3 | | | | |
| piroloculina sp. | | | | | | | | | | | | | | .3 | | | | |
| rifarina bradyi | | | | | | | | | | | | | | | | | | |
| riloculina tricarinata | | | 1 | | | | | | | | .2 | | | | | | | |
| vigerina auberiana and variant | 4 | 7 | 5 | 2 | 6 | 5 | 1 | 5 | 1 | 2 | .6 | 1 | | 1 | 3 | .8 | .2 | 8 |
| hollicki | | | | | 1 | .5 | .6 | 5 | 7 | 1 | 2 | 7 | 5 | 9 | 5 | 18 | 9 | 13 |
| hollicki | | | | | | | | | | | | | | | | | | |
| alvulineria humilis | .6 | | 1 | .6 | | | | | | | | | | | | | | |
| irgulina advena | .6 | .5 | | | 1 | | | | | 2 | 2 | 2 | | | .5 | .4 | 2 | |
| bradyi | | | | | | | | | | | | | | 1 | | | | |
| complanata | | | | | | | | | | | | | | | .5 | | | |

TABLE 35. Occurrences of Foraminifera in selected samples from Core 292 in percent of total population. Planktonic and benthonic populations computed separately.

| CORE 292 | DEPTH-3,216 M | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE | 1 | 3 | 8 | 13 | 15 | 18 | 19 | 22 | 27 | 32 | 37 | 42 | 46 | 51 | 56 | 61 | 65 | 68 | 73 | 77 | 81 | 84 | 87 | 90 |
| CM. FROM TOP OF CORE | 3-3.5 | 19.5-20 | 69.5-70 | 119.5-120 | 139.5-140 | 169.5-170 | 179.5-180 | 209.5-210 | 259.5-260 | 309.5-310 | 359.5-360 | 409.5-410 | 449.5-450 | 499.5-500 | 549.5-550 | 599.5-600 | 639.5-640 | 669.5-670 | 719.5-720 | 760-761.5 | 799.5-800 | 829.5-830 | 859.5-860 | 889.5-890 |
| PLANKTONIC POPULATION | 10,000 | 6,600 | 13,800 | 13,000 | 16,000 | 10,600 | 11,200 | 8,000 | 13,400 | 12,800 | 15,200 | 10,300 | 11,300 | 2,450 | 12,900 | 10,300 | 9,400 | 19,500 | 6,500 | 8,800 | 13,100 | 10,000 | 9,300 | 10,300 |
| Globigerina bulloides | 35 | 31 | 41 | 45 | 32 | 31 | 38 | 55 | 31 | 41 | 37 | 23 | 50 | 26 | 43 | 37 | 31 | 39 | 23 | 25 | 37 | 37 | 39 | 34 |
| G. eggeri | 8 | 23 | 11 | 15 | 25 | 27 | 15 | 19 | 20 | 25 | 17 | 14 | 20 | 30 | 10 | 23 | 23 | 22 | 34 | 14 | 25 | 11 | 10 | 24 |
| G. inflata | 18 | 24 | 8 | 7 | 15 | 14 | 7 | 6 | 16 | 8 | 12 | 25 | 11 | 25 | 5 | 8 | 17 | 12 | 25 | 22 | 12 | 21 | 25 | 11 |
| G pachyderma | 3 | 5 | 13 | 5 | 3 | 2 | 9 | 5 | 1 | 1 | 4 | .6 | 11 | 6 | 15 | 3 | 3 | 9 | 3 | 3 | 7 | 2 | .7 | 11 |
| G quinqueloba | 4 | 3 | 11 | 14 | 6 | 12 | 17 | 5 | 7 | 5 | 9 | 4 | 3 | 1 | 20 | 11 | 9 | 8 | 4 | 4 | 7 | 1 | 3 | 7 |
| Globigerinella aequilateralis | 1 | | | | | .3 | 1 | .4 | 5 | .3 | .6 | 6 | 6 | | | .6 | | | .5 | | .2 | .3 | 2 | .3 |
| Globigerinita glutinata | 3 | | 3 | 5 | 5 | 5 | 4 | 3 | 5 | 2 | 2 | 3 | .6 | 4 | 1 | 2 | 2 | 1 | 3 | 2 | 3 | 3 | 2 | 2 |
| Globigerinoides conglobata | | | | | | | | | | | .2 | R | | | | | | .3 | | | | | | |
| G. rubra | 9 | | 2 | .5 | 1 | 4 | 2 | 1 | 5 | .8 | 2 | 6 | 2 | 5 | 1 | 6 | 2 | .3 | 1 | 5 | .7 | 10 | 5 | 2 |
| G. sacculifera | | | | | | | | | | | | .3 | | | | | | | | | | | | |
| Globorotalia hirsuta | 3 | | | R | 1 | .6 | | 1 | 1 | 3 | 3 | 2 | | .3 | R | .3 | .6 | .6 | .5 | 3 | .5 | 3 | .3 | .3 |
| G menardii – tumida group | | | | | | | | | | | | R | | | | | | | | | | | | |
| G. punctulata | R | | | | R | 1 | | | | | | .6 | .3 | | | | | | | | | | .3 | .6 |
| G. scitula | 7 | | 10 | 8 | 9 | | 7 | 3 | 9 | 7 | 9 | 7 | 1 | 2 | 3 | 3 | 11 | 6 | 2 | 7 | 5 | 4 | 6 | 6 |
| G. truncatulinoides | 7 | | | | .8 | 4 | | .4 | 2 | 9 | 3 | 11 | 6 | .3 | R | 2 | R | 1 | 2 | 13 | 2 | 5 | 5 | 1 |
| Orbulina universa | 2 | | | | .8 | 1 | .6 | 2 | 1 | | 2 | 2 | 1 | 1 | 1 | 4 | 2 | .7 | 5 | 1 | 1 | 1 | 2 | 2 |
| [Sphaeroidina bulloides] | | | | | | | | | | | | | | | | | | R | | | | | | |
| BENTHONIC POPULATION | 70 | 200 | 190 | 230 | 250 | 160 | 185 | 90 | 80 | 150 | 130 | 100 | 170 | 130 | 70 | 200 | 60 | 275 | 165 | 80 | 220 | 500 | 100 | 65 |
| Anomalina sp | | | | | | | | | | | | | | | | | 2 | | | | | | | |
| Bolivina cf minuta | | | | | | | | | | | | | | | | | | | | 2 | | | | |
| B. pseudopunctata | | 3 | 2 | | .8 | | | 1 | | | | | 1 | 8 | 1 | | | | | | | | | |
| Bulimina aculeata | | | | | | | | | | | | | 1 | | | | | | | | | | | |
| Cassidulina carinata | | | | | | | | | | | | | 9 | | | | | | | | | | | |
| C. crassa | | | | | | | | | 1 | | | | | 3 | | | | 4 | | | | | | |
| C. subglobosa | | 1 | | | 3 | 13 | 1 | | 5 | 1 | 3 | 2 | 11 | 18 | | | | .7 | | 2 | | | | 2 |
| Chilostomella oolina | | 3 | | | | | | | | | 2 | | 1 | 7 | 1 | 4 | | 1 | 1 | | | | | |
| Cibicides kullenbergi | 18 | | | | | | | | | | | | | | 1 | | | | | | | | | |
| C. robertsonianus | 3 | | 1 | .8 | .8 | 4 | | 2 | | 7 | 8 | 8 | | 2 | 3 | | 6 | .4 | | | | .8 | 2 | |
| C. sp. | 1 | | 1 | 7 | 11 | 10 | 3 | 3 | 6 | 6 | 2 | 2 | 2 | .8 | | 2 | | 1 | .6 | 21 | 18 | | 4 | 5 |
| Ehrenbergina undulata | | | | | | 3 | | | 2 | | | | | | | | | | | | | | | |
| Eponides umbonatus and variants | 9 | 4 | 12 | 7 | 3 | 6 | 3 | 8 | 10 | 3 | 6 | 10 | 2 | .8 | 4 | 5 | | 1 | .6 | 12 | | 2 | 10 | 9 |
| Gyroidina lamarckiana | | | | | | 3 | | | | | | | | .8 | | | | | | | | | | |
| G. orbicularis | | | | | | | | | | 1 | | | | | | | | | | | | | | |
| G. soldanii variant | 6 | | 6 | 12 | 9 | | 2 | 8 | 9 | 1 | 3 | 2 | | | 7 | | 2 | 1 | .6 | 5 | 11 | 2 | 2 | 8 |
| Höglundina elegans | 3 | | | | | | 3 | | | | | | | | | | | | | | | | | |
| Eggerella bradyi | 1 | 3 | 5 | 3 | | | 4 | 1 | 3 | 7 | 3 | 10 | | 4 | | 2 | 2 | 2 | 4 | | 2 | | | |
| Laticarinina pauperata | 3 | | | | | | | | | | | | | .8 | | | | | | | | | | |
| Nonion barleeanum | 1 | 20 | 4 | 4 | 2 | | 2 | 1 | 3 | 3 | 9 | 2 | 6 | 11 | 11 | 7 | 5 | 4 | 5 | 7 | 2 | | 2 | 2 |
| N. formosum | 3 | | | .8 | | | | | | | | | | | | | 5 | .7 | | | | | | |
| N germanicum | | 19 | 12 | | 2 | 3 | 2 | | 1 | | | | | | | | | | | | | | | 2 |
| N. pompilioides | 1 | 6 | 2 | | .8 | 1 | | 10 | 4 | 5 | 8 | | 6 | 6 | 2 | 4 | | .7 | 1 | | 25 | 2 | 10 | 5 |
| Patellina corrugata | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| Planulina wuellerstorfi | 1 | 5 | 6 | 12 | 9 | 13 | 6 | 7 | 16 | 7 | 14 | 29 | 2 | | 6 | 3 | 10 | 5 | 1 | 23 | 9 | 2 | 23 | 13 |
| Epistominella exigua | 28 | 1 | 17 | 18 | 18 | 5 | 39 | 12 | 18 | 23 | 6 | 8 | 14 | | 8 | 15 | 5 | 11 | .6 | 2 | | 7 | 14 | 17 |
| E. umbonifera | | | | | 4 | 10 | | | | | | | | | | | | | | 2 | | | | 2 |
| Pullenia bulloides | 1 | 5 | 3 | 2 | 2 | | 1 | 7 | 1 | 6 | | 2 | 1 | 8 | | 1 | | 1 | 1 | | 2 | | 4 | 3 |
| P. quinqueloba | 1 | 1 | 2 | 3 | 2 | 3 | 1 | | 3 | 1 | 2 | 4 | 2 | 2 | 1 | 2 | 2 | .7 | 1 | | 2 | | 2 | 11 |
| P. sp. | | | | | | | 1 | 1 | | 4 | | | | | | | | | | 2 | | | | |
| Pyrgo murrhina | | 1 | 2 | 2 | 6 | 14 | | | 6 | | 2 | | 2 | | 1 | | 2 | .8 | | | 11 | | | 2 |
| P oblonga | 1 | 3 | 3 | .8 | .8 | | 2 | | | 4 | | | 2 | 4 | 4 | 3 | | | 9 | | 5 | 2 | | 2 |
| Quinqueloculina venusta | 6 | | 6 | .8 | .8 | 1 | 1 | | 4 | 4 | 3 | 10 | | | | | 2 | 1 | .6 | | 8 | .8 | 6 | 2 |
| Q cf. weaveri | | | 1 | | | | | | | 1 | 2 | | 1 | | | | | | | 7 | | | 2 | |
| Robulus | | | | .8 | .8 | | 2 | | | | | | | | | | | .4 | | | | | | 2 |
| Sigmoilina schlumbergeri | 3 | | | | 3 | | 2 | | | | 5 | 6 | 1 | | | | | | | 7 | | | 10 | 2 |
| S. tenuis | | | | | | | | | | | | | | | | | 2 | | | | | | | |
| Siphotextularia rolshauseni | 3 | 1 | 2 | 3 | .8 | 5 | 2 | 1 | 1 | | 2 | | 1 | | | 1 | | | | 5 | | .8 | | |
| Spiroloculina sp. | | | | .8 | | | | | 1 | 3 | | | | | | | | | | | | | | |
| Triloculina tricarinata | | 1 | 5 | 8 | 8 | 6 | 15 | 2 | 5 | 7 | | | 6 | 8 | 1 | 7 | 8 | 1 | .6 | | 2 | | | 3 |
| Uvigerina hollicki | | | 4 | 13 | 10 | 1 | 6 | 28 | | 3 | 22 | 6 | 24 | 16 | 45 | 41 | 10 | 61 | 72 | | 4 | 80 | | 9 |
| Valvulineria humilis | 5 | | | | | | | | | | | | | | | | | | | | | | | |
| Virgulina advena | | 1 | | 2 | | | | 1 | 1 | 1 | 2 | | 1 | | | 1 | 6 | 3 | .6 | | | | 8 | 2 |
| V. bradyi | | 23 | 1 | | 2 | | | 4 | | 1 | | | 1 | | | | 2 | | | | | | | |
| V. complanata | | | | | | 1 | | | | | | | | .8 | | | | 1 | | 2 | | | | |

TABLE 36. Occurrences of Foraminifera in selected samples from Core 293 in percent of total population. Planktonic and benthonic populations computed separately.

CORE 293 DEPTH-3,485 M.

| SAMPLE | 1 | 3 | 8 | 13 | 18 | 19 | 22 | 27 | 30 | 34 | 39 | 44 | 48 | 53 | 56 | 61 | 66 | 71 | 72 | 74 | 77 | 81 | 82 | 84 | 89 | 94 | 96 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 1-1.5 | 19.5-20 | 69.5-70 | 119.5-120 | 169.5-178 | 179.5-180 | 209.5-210 | 259.5-260 | 289.5-290 | 329.5-330 | 379.5-380 | 429.5-430 | 469.5-470 | 519.5-520 | 550.5-551 | 599.5-600 | 649.5-650 | 699.5-700 | 709.5-710 | 729.5-730 | 759.5-760 | 799.5-800 | 809.5-810 | 829.5-830 | 879.5-880 | 929.5-930 | 949.5-950 |
| PLANKTONIC POPULATION | 9,600 | 10,100 | 10,400 | 9,850 | 15,200 | 12,400 | 11,700 | 8,000 | 6,950 | 10,600 | 6,000 | 9,000 | 9,000 | 2,700 | 15,900 | 10,700 | 16,000 | 10,200 | 13,800 | 9,250 | 11,100 | 10,200 | 11,000 | 13,200 | 14,800 | 5,100 | 3,200 |
| Globigerina bulloides | 41 | 36 | 23 | 46 | 34 | 37 | 43 | 31 | 36 | 23 | 36 | 24 | 46 | 35 | 52 | 34 | 34 | 35 | 39 | 30 | 21 | 43 | 71 | 35 | 46 | 20 | 36 |
| G digitata |  |  |  |  |  |  |  |  |  |  | R |  |  |  |  |  |  |  |  |  |  | R |  |  |  |  |  |
| G. eggeri | 9 | 15 | 36 | 10 | 18 | 23 | 15 | 32 | 19 | 25 | 18 | 17 | 18 | 34 | 18 | 29 | 28 | 29 | 16 | 20 | 23 | 6 | 4 | 17 | 24 | 19 | 36 |
| G inflata | 14 | 4 | 17 | 6 | 13 | 17 | 12 | 19 | 15 | 8 | 16 | 32 | 8 | 14 | 7 | 7 | 8 | 16 | 18 | 19 | 29 | 26 | 8 | 22 | 10 | 12 | 11 |
| G pachyderma | .7 | 25 | 10 | 14 | 7 | 4 | 7 | 3 | 4 | 2 |  | .4 | 15 | 5 | 9 | 4 | 5 | 2 | 2 | .7 |  | 2 | 3 | 1 | 4 | 40 | 5 |
| G. quinqueloba | 3 | 11 | 3 | 10 | 10 | 6 | 6 | .8 | 4 | 14 | 7 | 1 | 4 |  | 5 | 6 | 12 | 3 | 4 | 2 | 7 | 3 | 5 | 3 | 4 | 6 | 4 |
| Globigerinella aequilateralis | 2 | .2 |  |  |  | .3 | .3 |  | .5 |  |  | 1 |  | .6 | .2 | .3 | .4 |  |  |  | .6 | .3 |  | .5 |  |  |  |
| Globigerinita glutinata | 2 | 1 | 2 | 1 | 5 | 5 | 4 | .8 | 6 | 4 | .5 | 1 | 1 | 2 | 1 | 4 | 3 | 3 | 2 | 2 | 2 |  | .6 | 3 | 3 | .6 | .5 |
| Globigerinoides conglobata |  |  |  |  |  |  |  |  |  |  |  | .4 | .4 |  | .2 | .3 |  |  |  |  |  |  | R |  |  |  |  |
| G rubra | 6 | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 2 | 2 | .5 | 7 | 4 | 4 | 2 | 5 | 2 |  | 1 | 7 | 4 | 3 |  | 1 | 1 | .6 | 2 |
| G sacculifera | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Globorotalia hirsuta | 3 | .6 | .3 |  | .8 | 2 | R | 1 | 1 | 1 | 3 | 2 | R | .7 | 1 | .3 | R | .6 | .5 | .7 | .6 |  | R | R | R |  | .5 |
| G menardii-tumida group |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |
| G punctulata |  | .3 |  |  | R | .5 |  |  |  |  |  |  | R |  |  |  | R |  |  |  |  | 2 | R |  |  |  |  |
| G scitula | 7 | 5 | 7 | 10 | 8 | 3 | 11 | 6 | 9 | 8 | 8 | 5 | 1 | 1 | 3 | 6 | 6 | 6 | 9 | 11 | 7 | 6 | 6 | 8 | 5 | 2 | R |
| G. truncatulinoides | 10 | 2 |  | .3 | .8 | 2 | R | R | 5 | 12 | 10 | 7 | 1 | .7 | R | 2 | .8 | 3 | 6 | 5 | 1 | 6 | 1 | 9 | 3 |  | 1 |
| Orbulina universa | 2 |  |  | .6 | .4 | .5 |  | 2 |  |  | .5 | 1 | .4 | 3 | .6 | 3 | .8 | 4 | 2 | 1 | 3 | 3 | .6 | 1 |  | 1 | 6 |
| [Sphaeroidina bulloides] |  | R |  | R |  |  |  |  |  |  |  |  |  |  |  |  |  | R |  |  |  |  |  |  |  |  |  |
| BENTHONIC POPULATION | 65 | 85 | 200 | 185 | 155 | 115 | 220 | 215 | 90 | 100 | 50 | 60 | 90 | 50 | 75 | 220 | 160 | 135 | 150 | 195 | 65 | 75 | 70 | 145 | 120 | 50 | 215 |
| Anomalina sp |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  | .6 |  |  |  |  | 5 |  |  |  |  |  |
| Bolivina cf minuta |  |  |  | 2 | .7 |  |  |  |  |  |  |  |  |  |  |  | .6 |  |  |  |  |  | 1 |  |  |  |  |
| B. pseudopunctata |  | 2 | 5 | 1 |  | 1 |  |  |  | 4 |  |  | 5 | 24 | 7 |  |  |  |  |  |  |  |  |  |  |  |  |
| Bulimina alazanensis | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | .6 |  |  |  |  |  |  |  |  |  |  |
| Cassidulina carinata |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  | 1 |  |  |  |  |  |  |  |  |  |  | 2 |  |
| C. crassa |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |
| C. subglobosa |  |  |  |  | 2 | 3 |  |  |  |  | 4 | 3 | 2 | 2 |  |  | .6 | .8 |  |  |  |  | 4 | 4 | 5 |  |  |
| Chilostomella oolina |  | 2 | 2 |  |  |  |  | 4 |  |  |  |  | 1 |  | 3 | 1 | 2 | 2 |  |  | 2 | 3 | 3 | 1 | 3 |  | 3 |
| Cibicides kullenbergi | 24 |  |  |  |  |  |  |  |  |  | 2 | 5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| C. robertsonianus |  |  |  |  | 3 | 1 | 1 | 2 |  |  | 2 | 8 | 1 |  | 1 | 2 | 1 | .8 | 1 | 1 |  |  |  | 3 | 2 |  | 1 |
| C. sp. |  | 7 |  | 1 | 9 | 3 | 1 | 1 |  | 8 | 2 |  | 1 |  |  | 2 | .6 |  | 4 | 1 | 3 | 3 | 1 | 3 | 14 | 2 | 5 |
| Ehrenbergina undulata |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eponides umbonatus and variants | 6 | 2 | 5 | 9 | 12 | 8 | 3 | 6 | 7 | 4 | 8 | 7 | 6 | 2 | 13 | 4 | 3 | 8 | 3 | 5 |  | 11 | 6 | 8 | 8 | 2 | 1 |
| Gyroidina lamarckiana | 3 | 2 | 1 |  | .7 |  | 1 |  |  |  |  |  |  |  |  |  |  | .8 |  |  |  |  |  | 3 |  |  |  |
| G. soldanii variant |  | 2 | 1 | 7 | 6 | 8 | 12 | 1 | 7 | 4 | 2 | 5 | 2 |  | 3 |  |  | 2 | 4 | 1 | 2 |  | 6 | 4 | 14 | 2 |  |
| Höglundina elegans |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eggerella bradyi |  | 10 | 2 | 1 | 3 | 2 | 5 | 3 | 18 | 6 | 6 | 5 | 5 | 4 | 1 | 3 | 2 | 6 | 5 | 2 | 3 |  | 3 | 3 | 2 | 6 |  |
| Laticarinina pauperata |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Nonion barleeanum |  | 7 | 9 | 7 | 3 | 3 | 1 | 4 | 11 | 6 | 2 | 3 | 10 | 6 | 3 | 8 | 2 | 5 |  |  | 3 |  | 7 | 7 | 2 | 6 | 6 |
| N. formosum |  |  | 1 |  | .7 |  | 2 | 2 |  | 2 |  | 2 |  | 2 | 1 |  |  |  | 1 |  |  | 11 | 1 | 1 |  |  | 1 |
| N germanicum |  | 7 | 18 | 5 | 3 | 2 | 2 | 3 |  | 2 |  |  |  |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |
| N. pompilioides |  | 2 | 19 | 9 | 3 | 6 | 4 | 5 | 7 |  | 2 | 2 | 8 | 14 | 8 | 4 | 2 | 4 | 1 |  | 8 | 3 | 6 | 10 | 14 | 2 | 2 |
| Planulina wuellerstorfi | 12 | 12 | 1 | 2 | 12 | 11 | 5 | 6 | 7 | 10 | 19 | 18 | 6 |  | 9 | 7 | 2 | 5 | 20 | 7 | 11 | 21 | 17 | 10 | 10 | 22 | 7 |
| Epistominella exigua | 24 | 14 |  | 7 | 7 | 7 | 15 | 1 | 11 | 15 | 6 | 11 | 12 |  | 12 | 19 | 6 | 7 | 18 | 2 | 11 | 16 | 7 | 4 | 2 | 10 | 7 |
| E. umbonifera |  |  |  | 1 | .7 | 3 | 1 |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |  | 1 |
| Pullenia bulloides |  | 2 | 6 | 8 | 3 | 3 | 6 | 1 |  | 4 | 2 | 3 | 2 | 4 |  | 2 | 2 | 5 |  |  | 2 |  | 7 | 1 |  | 10 | 6 |
| P. quinqueloba | 3 |  | 2 | 1 | .7 | 2 | 1 | 3 | 2 | 4 | 4 | 2 |  | 4 | 5 | 1 | 1 | 2 | 4 | 1 |  | 3 | 3 |  | 2 | 4 |  |
| P. sp. |  |  |  | 2 | .7 |  |  |  |  |  |  | 2 |  |  | 3 |  |  | .8 |  |  |  |  | 3 |  | 2 |  | 1 |
| Pyrgo murrhina |  | 2 | 2 | 3 | 3 | 4 | 5 | 2 | 5 | 4 | 2 |  | 5 |  | 1 |  | 1 | .8 | 1 |  |  |  |  | 4 | 3 |  | 2 |
| P. oblonga |  |  |  | 4 | 3 | 3 | 4 | 4 | 7 | 2 |  | 2 | 1 | 8 | 4 |  | 3 | 8 |  | 1 | 3 |  | 3 | 1 |  | 4 | 5 |
| Quinqueloculina venusta | 3 | 5 |  | 2 | 1 | 5 | 2 | 3 | 11 | 6 | 4 | 3 |  |  | 1 | 3 | .6 | .8 |  | 2 |  | 5 | 5 | 1 | 7 | 6 | 2 |
| Q. cf. weaveri |  |  |  |  | .7 |  |  |  |  | 2 | 2 | 5 |  |  |  |  |  |  |  | 1 |  | 3 |  |  | 2 |  |  |
| Robulus |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |
| Sigmoilina schlumbergeri | 15 |  |  |  |  |  |  |  |  |  |  | 5 |  |  |  |  |  |  |  |  |  | 16 |  | 1 |  |  |  |
| S. tenuis |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 | .8 |  |  |  |  |  | 1 |  |  |  |
| Siphotextularia rolshauseni | 3 |  | 1 | 3 | .7 | 4 | 5 | 1 |  | 2 | 2 | 3 | 3 |  |  |  | .6 | .8 |  | 2 |  | 3 |  |  |  |  |  |
| Spiroloculina sp. |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 |  |  |  |
| Triloculina tricarinata |  |  | 3 | 9 | 6 | 10 | 17 | 6 | 5 | 8 |  |  | 2 | 18 | 11 | 10 | 2 |  | 4 |  |  |  | 10 | 7 | 2 |  | 1 |
| Uvigerina hollicki |  | 10 | 1 | 2 | 14 | 3 | 8 | 32 |  | 2 | 25 | 5 | 27 | 10 | 13 | 32 | 63 | 42 | 28 |  |  |  |  |  | 5 | 18 | 46 |
| U. hollicki variant |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 72 | 46 |  |  |  |  |  |  |
| Valvulineria humilis |  | 2 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  |  |  | 3 |  | 2 |  | 4 |  | 2 |  |  |  |  |  | 1 | 1 | .8 | 4 |  | 3 |  | 1 | 6 |  |  |  |
| V. bradyi | 3 | 5 | 20 | 10 | 3 | 6 |  | 4 |  | 4 |  |  |  |  |  | 1 |  |  |  |  | 2 |  | 1 | 13 |  | 2 | 4 |
| V. complanata |  |  |  |  |  |  |  |  |  |  |  |  |  | 2 |  |  |  |  | 1 |  |  |  |  | 1 |  |  |  |

TABLE 37. Occurrences of Foraminifera in sele samples from Core 296 in percent of total populat Planktonic and benthonic populations computed separately.

CORE 296 DEPTH-3,736 M.

| SAMPLE | 1 | 5 | 10 | 12 | 14 | 19 | 24 | 29 | 31 | 36 | 41 | 46 | 51 | 56 | 58 | 61 | 66 | 69 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CM. FROM TOP OF CORE | 0.5-1 | 39.5-40 | 89.5-90 | 109.5-110 | 129.5-130 | 179.5-180 | 229.5-230 | 279.5-280 | 299.5-300 | 349.5-350 | 399.5-400 | 449.5-450 | 499.5-500 | 549.5-550 | 569.5-570 | 599.5-600 | 649.5-650 | 679.5-680 |
| PLANKTONIC POPULATION | 11,000 | 11,200 | 22,200 | 16,900 | 19,100 | 24,000 | 12,900 | 19,900 | 17,700 | 24,200 | 26,600 | 16,000 | 25,400 | 14,100 | 3,400 | 14,600 | 13,600 | 15,700 |
| Globigerina bulloides | 38 | 39 | 50 | 40 | 37 | 38 | 26 | 23 | 44 | 27 | 37 | 39 | 43 | 26 | 33 | 36 | 30 | 44 |
| G. eggeri | 10 | 15 | 11 | 15 | 18 | 23 | 27 | 23 | 29 | 28 | 23 | 19 | 14 | 30 | 25 | 26 | 38 | 24 |
| G inflata | 14 | 11 | 8 | 9 | 14 | 15 | 12 | 18 | 11 | 19 | 16 | 19 | 14 | 8 | 9 | 13 | 15 | 10 |
| G pachyderma | 2 | 8 | 9 | 8 | 4 | 2 | .2 | 3 | 4 | 6 | 3 | 2 | 3 | 7 | 17 | 9 | 3 | 4 |
| G. quinqueloba | 1 | 10 | 6 | 10 | 6 | 4 | 5 | .2 | 2 | 4 | 2 | 3 | 5 | 8 | 6 | 2 | 1 | 2 |
| Globigerinella aequilateralis | 1 |  |  | .6 | .5 | .3 | 2 | 1 | .4 |  | .1 | 1 | .3 |  |  |  | .2 |  |
| Globigerinita glutinata | 5 | 4 | 4 | 5 | 4 | 3 | 3 | 2 | 1 | 3 | 3 | 2 | 3 | 6 | 3 | 2 | 3 | 4 |
| Globigerinoides conglobata | R |  |  |  |  |  | .5 | R |  |  |  |  |  |  |  |  |  |  |
| G rubra | 5 | 3 | 1 | .2 | 3 | 3 | 3 | 11 | 3 | 4 | 5 | 3 | 4 | 2 | 1 | 2 | .7 | .8 |
| G sacculifera | 3 |  |  |  |  |  |  | .8 |  | .3 |  | .2 |  |  |  |  |  | .2 |
| Globorotalia hirsuta | 5 | .3 |  | .2 | 1 | 1 | 2 | 1 | .7 | .3 | .5 | .2 | .8 |  |  | R | .5 |  |
| G. menardii |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G punctulata |  |  |  | .2 | 5 |  | .2 | .2 |  |  |  | .2 |  | R | .7 |  |  | .4 |
| G scitula | 6 | 8 | 11 | 14 | 8 | 6 | 4 | 4 | 3 | 6 | 5 | 5 | 6 | 10 | 3 | 6 | 4 | 9 |
| G truncatulinoides | 11 | 3 | .1 | .8 | 3 | 4 | 13 | 11 | .7 | 1 | 4 | 5 | 6 | 2 | .5 | 3 | 1 | 2 |
| Orbulina universa | .6 | .3 | .6 | .8 | .8 | 1 | 4 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 1 | R | 2 | .6 |
| [Sphaeroidina bulloides] |  |  |  |  | R |  |  |  |  | R |  |  |  |  |  |  | R |  |
| BENTHONIC POPULATION | 100 | 90 | 170 | 180 | 300 | 85 | 90 | 80 | 350 | 380 | 120 | 130 | 150 | 90 | 75 | 160 | 120 | 100 |
| Anomalina sp. |  |  |  |  |  |  |  |  |  |  |  | 1 | 4 | 5 |  |  |  |  |
| Bolivina cf minuta | 1 |  |  |  | 1 |  |  |  |  | .5 |  | 1 |  |  |  |  | 2 | 2 |
| B. pseudopunctata |  | 1 |  |  | 1 |  |  | 5 | 6 |  |  |  |  |  |  |  | 2 |  |
| Bulimina alazanensis |  |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |
| Cassidulina carinata |  |  |  |  |  |  |  | 2 |  |  |  |  |  |  |  |  |  |  |
| C crassa |  |  | 1 |  |  | 1 |  | 5 | 2 |  |  | 1 |  |  |  |  |  |  |
| C. subglobosa | 4 | 3 | 4 | 3 | 3 | 2 | 7 | 7 | 5 | 1 | 2 | 7 | 7 | 14 | 12 | 2 | 10 | 8 |
| Chilostomella oolina |  |  |  |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |
| Cibicides kullenbergi | 17 |  |  |  |  |  |  |  |  | 1 |  |  | 1 |  |  |  | 2 |  |
| C. robertsonianus | 1 | 3 | 1 |  | 1 |  |  |  |  |  | .8 | 1 | 3 |  |  | .6 |  |  |
| C. sp. | 2 | 3 | 4 | 3 | 1 | 6 |  | 2 | 6 | 2 | 2 | 4 | 5 | 5 |  | 2 | 3 | 15 |
| Ehrenbergina undulata |  |  |  | 1 | .7 | 3 |  |  | 3 | 2 |  | 1 | 1 | 4 |  | .6 | 3 | 6 |
| Eponides umbonatus and variants | 12 | 8 | 13 | 14 | 8 | 19 | 1 | 5 | 6 | 1 | .8 | 1 | 7 | 7 | 6 | 6 | 5 | 6 |
| Gyroidina lamarckiana |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| G. orbicularis | 2 | 2 |  |  |  |  |  | 2 |  |  | .8 | 1 |  |  | 3 | 2 | 2 |  |
| G. soldanii variant | 4 | 3 | 7 | 9 | 12 | 9 | 1 | 5 | 2 | 2 | 2 | 8 | 8 | 16 |  | .6 | 2 |  |
| Höglundina elegans | 3 | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Eggerella bradyi | 2 | 5 | 6 | 3 | 3 | 7 | 2 | 7 | 6 | 4 | 6 | 1 | 3 | 5 | 3 | 5 | 11 | 10 |
| Nonion barleeanum | 2 | 9 | 1 | 3 | 3 | 1 | 3 | 2 | 3 | 2 |  |  |  | 2 |  | 9 | 2 |  |
| N. formosum |  | 4 |  |  |  |  |  |  | .6 |  |  |  |  |  |  |  |  |  |
| N. germanicum | 1 | 4 | 8 | 3 | 4 |  |  | 2 |  |  |  |  |  | 2 |  |  |  |  |
| N pompilioides |  | 1 | 5 | 4 | 4 | 2 | 4 |  | 7 | 7 | .8 | 1 | 3 |  | 2 | 5 | 4 | 6 |
| Planulina wuellerstorfi | 10 | 4 | 2 | 1 | 3 | 6 | 13 | 22 | 4 | 5 | 7 | 16 | 18 | 2 | 4 | 10 | 15 | 19 |
| Epistominella exigua | 15 | 21 | 8 | 6 | 11 | 5 | 8 | 10 | 21 | 6 | 17 | 33 | 3 | 14 | 29 | 28 | 28 | 21 |
| E. umbonifera | 4 | 8 | 6 | 2 | .7 | 1 |  |  |  |  | 2 | 1 | 11 |  | 5 | .6 | 2 |  |
| Pullenia bulloides | 4 | 4 | 14 | 6 | 7 | 9 | 1 |  | 7 | 7 | 2 | 1 | 4 | 9 | 9 | 5 | 2 | 2 |
| P quinqueloba | 3 | 2 |  | 1 | 3 | 1 | 3 | 2 | 1 | 2 | 2 | 1 | 7 | 5 | 3 |  | 2 |  |
| P. sp. | 1 | 1 |  | 1 |  |  | 2 |  |  | 1 |  |  | 3 |  |  | 2 | 3 | 2 |
| Pyrgo murrhina |  |  | 1 | 4 | 1 | 5 |  |  | .6 | 3 | 2 | 1 | 4 | 2 |  | 2 |  |  |
| P. oblonga | 2 | 2 |  |  |  |  |  | 5 | 3 | 2 | 2 |  |  | 2 | 1 |  |  |  |
| Quinqueloculina venusta |  |  |  | 1 | .7 | 1 | 2 |  |  | 2 | 2 |  | 1 | 5 | 3 | .6 |  |  |
| Q. cf. weaveri | 1 |  |  |  |  |  | 1 |  |  | .5 | .8 |  |  |  |  |  |  |  |
| Robulus | 1 |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Sigmoilina schlumbergeri |  |  | 1 |  |  | 1 |  |  |  |  |  |  |  |  |  |  |  |  |
| S. tenuis |  |  |  |  |  | 2 |  |  |  | .5 |  | 1 | 1 |  |  |  |  |  |
| Siphotextularia rolshauseni | 4 |  | 1 | 1 | 3 |  | 2 |  |  | 2 | .8 | 4 | 1 |  |  |  |  | 2 |
| Triloculina tricarinata |  | 1 | 1 | 4 | 2 | 2 | 2 |  | 1 | 4 |  |  |  |  |  |  |  |  |
| Uvigerina hollicki |  | 8 | 12 |  | 27 | 7 | 43 | 7 | 15 | 42 | 42 | 1 | 4 | 2 | 19 | 18 | 2 |  |
| Valvulineria humilis | 3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Virgulina advena |  | 1 |  |  |  | 6 |  |  |  |  | 2 |  |  |  |  | .6 |  |  |
| V. bradyi | 1 |  |  | 1 |  |  |  | 5 | 1 | 1 |  | 1 |  |  |  |  | 2 |  |
| V. complanata |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |  |

tions than the latitude at which this core was collected, separated by typical mid-latitude assemblages.

**Core 293.** There are five faunal shifts in this core from mid-latitude to higher latitude assemblages.

**Core 296** has four faunal higher-latitude faunas; the upper one is bounded above and below by what appear to be normal mid-latitude faunas. The lower faunas separating the higher-latitude assemblages are less characteristic of mid-latitudes.

The bases for differentiating the faunas in these latter cores are similar to those described for Cores 280 and 284.

TABLE 38. Occurrences of Foraminifera in surface sediment samples in percent of total population. Planktonic and benthonic populations computed separately.

| | ALBATROSS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ATLANTIS | | | | | | | | | | SAN PABLO | | REHOBETH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAMPLE No. | 224A | 225A | 226A | 228A | 230A | 232A | 233A | 234A | 235A | 236A | 238A | 240A | 242A | 243A | 246A | 247A | 252A | 257A | 258A | 261A | 265A | 267A | 269A | 270A | 272A | 279A | 280A | 281A | 283A | 284A | 285A | 286A | 288A | 289A | 292A | 294A | 297A | 4631 | 4633 | 4635 | 4637 | 4736 | 4739 | 4740 | 4741 | 4742 | 4743 | 3-16 | 3-47 | 3-29 | 3-32 | 3-38 | 3-41 |
| DEPTH IN METERS | 2810 | 2973 | 3100 | 4280 | 5500 | 4975 | 4125 | 3577 | 4560 | 5065 | 7315 | 7500 | 3620 | 3740 | 3210 | 4285 | 4480 | 4470 | 4554 | 5128 | 5832 | 2105 | 5855 | 5760 | 5450 | 4663 | 4256 | 4281 | 4940 | 4257 | 4570 | 4060 | 2684 | 2640 | 3216 | 3749 | 5980 | 1832 | 3243 | 3611 | 4182 | 4420 | 4365 | 5326 | 4526 | 5136 | 5532 | 4755 | 3017 | 2761 | 3383 | 3109 | 4590 |
| PLANKTONIC POPULATION | 10,600 | 9,800 | 11,100 | 33,800 | 1,400 | 5,300 | 22,400 | 46,700 | 57,100 | 47,900 | | 5,000 | 38,500 | 68,100 | 29,300 | 22,400 | 6,800 | 19,200 | 13,800 | 90 | 33 | 22,000 | 9 | 3 | | 15,200 | 26,200 | 23,400 | 5,200 | 11,700 | 13,900 | 12,700 | 10,800 | 8,900 | 22,600 | 20,400 | | | | | | | | | | | | | | | | | |
| Candeina nitida | | | | | | | | | | | | | | | | | | .3 | 5 | | | .3 | | | | | | | | | | | | | | | | .8 | .2 | | | | | | .7 | 7 | | | | | | | |
| Globigerina bulloides | 26 | 14 | 18 | 5 | 2 | 6 | 5 | 2 | 1 | .5 | P | .8 | 8 | 1 | 1 | 3 | .5 | 4 | 3 | 3 | 51 | 1 | 33 | 33 | P | 27 | 35 | 32 | 31 | 39 | 46 | 45 | 40 | 38 | 53 | 41 | R | 24 | 26 | 28 | 38 | 27 | 30 | 4 | 7 | 9 | 4 | 29 | 35 | 67 | 29 | 36 | 27 |
| G. digitata | | .3 | | | | | | | | | | | .3 | .2 | .2 | | | .3 | | | | | | | | | | | | | | | | | | | | | .2 | | | | | | | | | | | | | | |
| G. eggeri | 25 | 27 | 13 | 8 | 20 | 24 | 11 | 7 | 8 | 12 | | 22 | .7 | 3 | 3 | 3 | 6 | 8 | 13 | 29 | | 6 | | | | .8 | 6 | 4 | 5 | 10 | 7 | 6 | 8 | 7 | 2 | 7 | | .8 | 1 | 2 | 2 | 1 | 3 | 1 | | .7 | 1 | .2 | 7 | 3 | 5 | 2 | 3 |
| G. inflata | 30 | 34 | 15 | 6 | | .6 | | | | .5 | | | | | | | | | | | 9 | | 22 | 33 | P | 20 | 15 | 17 | 18 | 15 | 13 | 16 | 19 | 21 | 13 | 14 | A | 12 | 11 | 13 | 10 | 8 | 8 | 9 | 1 | 3 | 7 | 6 | 11 | 5 | 21 | 18 | 9 |
| G. pachyderma | | | | | | | | | | | | | | | | | | | | | | | | | | | | .3 | .3 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | R | | .2 | | | .8 | .2 | .4 | | | | | 20 | .8 | 29 | .5 | .3 |
| G. quinqueloba | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | .5 | .3 | .3 | | 1 | | | | | .2 | | | | | | | | | 15 | 13 | 4 | .3 | |
| Globigerinella aequilateralis | | | 1 | 2 | | | 2 | 3 | 2 | 2 | | | 2 | 3 | 3 | 2 | 1 | 3 | .5 | | | 4 | | | | 1 | 3 | .8 | .3 | | 1 | .3 | .3 | | .4 | 2 | | 3 | 2 | 2 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 2 | .5 | | | 1 | 1 |
| Globigerinita glutinata | | | .6 | 5 | | | | 2 | 6 | | | | 8 | 6 | 5 | 4 | .5 | 4 | | | 3 | 5 | | | P | 3 | 3 | 6 | 2 | 1 | 2 | | | | 2 | 5 | | .5 | 6 | 5 | | 4 | 5 | 3 | 3 | 1 | 1 | 5 | 3 | 11 | 5 | 5 | 16 |
| Globigerinoides conglobata | | | .3 | .4 | .6 | .6 | 1 | .5 | .2 | .5 | | .4 | | .2 | .4 | .6 | 2 | .7 | 4 | 1 | | .6 | | | | .8 | .5 | .3 | 1 | .5 | .2 | .8 | 1 | | | | | .5 | | 1 | 5 | 1 | .4 | 3 | 1 | | 1 | 1 | | | | .3 | 1 |
| G. rubra | 3 | 4 | 18 | 32 | 6 | 7 | 15 | 22 | 26 | 7 | P | .8 | 38 | 39 | 37 | 30 | 17 | 41 | 28 | 3 | 21 | 47 | 22 | 33 | P | 23 | 18 | 16 | 23 | 13 | 11 | 12 | 11 | 13 | 5 | 7 | R | 35 | 25 | 15 | 23 | 24 | 25 | 43 | 65 | 56 | 51 | 27 | 3 | .8 | .8 | 16 | 21 |
| G. sacculifera | 4 | 5 | 13 | 22 | 2 | 31 | 47 | 51 | 38 | 39 | P | 2 | 25 | 30 | 36 | 35 | 33 | 29 | 33 | | | 28 | 11 | | | 3 | 3 | 3 | 2 | 2 | 3 | 1 | 1 | 1 | .8 | 2 | | 2 | 4 | 9 | 10 | 9 | 10 | 14 | 10 | 9 | 4 | 9 | .3 | | | 2 | 3 |
| Globorotalia hirsuta | | .3 | | .4 | .6 | | | | | | | | | | | | | | | | | | | | | 7 | 5 | 7 | 7 | 6 | 8 | 6 | 6 | 7 | 6 | 3 | | 8 | 4 | 4 | 2 | 6 | 4 | .7 | .7 | .4 | 3 | 9 | 2 | R | 3 | 6 | 7 |
| G. menardii | 7 | 10 | 18 | 16 | | 13 | 9 | 5 | 8 | 19 | | 20 | 8 | 9 | 6 | 8 | 16 | 5 | 10 | 1 | | 3 | | | | .8 | | R | .6 | 2 | R | | R | | | | | | | | | | | .4 | | | | | | | | R | .3 |
| G. punctulata | .3 | 2 | .3 | 1 | 1 | 2 | | 1 | | 1 | | 1 | .7 | .8 | | .6 | .5 | .7 | .5 | 6 | | | | | | .8 | | | | | | | | | | | | .5 | | .6 | | | .8 | 2 | | .7 | .4 | | .3 | | 3 | | .6 |
| G. scitula | .6 | | .3 | .4 | | | | .5 | | | | | 1 | .4 | | .6 | | .3 | .5 | | 9 | | 11 | | | 2 | 2 | 2 | .6 | 2 | 1 | 4 | 3 | 4 | 3 | 5 | | .8 | 5 | 6 | 2 | 2 | 1 | .4 | .5 | | | | 2 | | .8 | 3 | |
| G. truncatulinoides | .3 | 2 | | .8 | | 2 | 1 | .3 | .2 | .3 | P | .4 | | | .2 | 2 | | | | | 3 | .6 | | | P | 8 | 9 | 11 | 7 | 6 | 4 | 6 | 9 | 6 | 12 | 11 | | 8 | 16 | 11 | 6 | 11 | 7 | 11 | 3 | 11 | 20 | 10 | 1 | | 1 | 8 | 9 |
| G. tumida | | | | | 61 | 11 | 2 | .5 | 3 | 7 | | 33 | 2 | 1 | 3 | 4 | 14 | 2 | 2 | 38 | | .6 | | | | | | R | .3 | .3 | | | | | | | | | | | | | | 3 | .2 | | | | | | | | |
| Orbulina universa | 2 | 2 | 3 | 2 | .6 | | 5 | 2 | 2 | .8 | | | 1 | 2 | 2 | 3 | .5 | 1 | 2 | | 3 | 1 | | | | 2 | 2 | .5 | .3 | .3 | 1 | .5 | .6 | .7 | | 1 | | 3 | .2 | 2 | .3 | 2 | 2 | 2 | 4 | 4 | 3 | 2 | .5 | R | .3 | .3 | .6 |
| Pulleniatina obliquiloculata | .3 | | | R | 4 | 2 | 2 | 2 | 4 | 11 | P | 15 | 5 | 4 | 3 | 5 | 9 | .3 | 3 | 7 | | .3 | | | | | | .3 | 1 | | .2 | | | | | | | | | | .3 | 1 | .8 | | | | | .4 | .8 | R | | .3 | .3 |
| Sphaeroidinella dehiscens | | | .3 | R | 3 | 1 | | | .5 | R | | 4 | .3 | .8 | | | .5 | | .5 | 12 | | .3 | | | | .4 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| BENTHONIC POPULATION | 155 | 160 | 120 | 41 | 235 | 160 | 125 | 145 | 125 | 155 | 2 | 130 | 92 | 46 | 59 | 55 | 63 | 155 | 125 | 165 | 0 | + | 2 | 0 | 8 | 55 | 150 | 106 | 78 | 135 | 200 | 120 | 86 | 95 | 63 | 52 | 24 | | | | | | | | | | | | | | | | |
| Anomalina sp. | | .6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .7 | | | | | | | | | | | |
| Bolivina cf. minuta | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | 1 | 2 | | | | | | | | | | | | | 1 | |
| B. pseudopunctata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .8 | | | | |
| B. subaenariensis | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bulimina aculeata | .6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | |
| B. alazanensis | 2 | 3 | .8 | | | | .8 | 1 | | | | | | | 2 | | | | | | | | | | | .7 | .7 | | | | | | | | | | | | 10 | | | | | | | | | | | | | | |
| B. translucens | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .7 | .7 | | | | | | | | | | | 4 | | | | | | | | | | | | |
| Cassidulina carinata | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 8 | | | | |
| C. crassa | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 17 | | | | | | | | | | | .8 | | 2 | | |
| C. subglobosa | | | | 5 | 2 | .6 | | 6 | 3 | 10 | | 8 | 17 | 2 | 12 | 5 | 2 | 1 | | 2 | | 5 | | | | 9 | 5 | 3 | 8 | 6 | 8 | 10 | | 1 | | 6 | | 6 | 2 | 7 | 11 | 3 | | 1 | 9 | 2 | 12 | | 4 | | | 3 | 1 |
| Cibicides kullenbergi | .6 | | 6 | | | | | 5 | | | | | | 4 | 7 | | | | | | | 5 | | | | | .7 | 2 | | | | 2 | 5 | 5 | 20 | 14 | | | 2 | 15 | 3 | .7 | | | | | | | 2 | 1 | 17 | 22 | |
| C. robertsonianus | 4 | 6 | 4 | | .4 | .6 | 3 | 1 | | 1 | | 2 | | 2 | | | | | | | | 5 | | | | | 2 | 5 | 6 | 2 | 2 | 2 | 5 | 4 | 8 | 8 | | 6 | 2 | 1 | 2 | 3 | 4 | | | | | | 2 | | 2 | 3 | 7 |
| C. sp. | 2 | .6 | 6 | 2 | | | .8 | .7 | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 | | | | 2 | | | | | | | | | | 2 | | 2 | 1 | |
| Discorbis williamsoni | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | .8 | | | | |
| Eggerella bradyi | .6 | | | | 1 | 4 | .8 | .7 | | | | .8 | 4 | 4 | | 4 | 2 | .6 | .8 | | | | | | | 2 | 3 | 2 | 1 | 4 | 5 | | | | | 4 | 38 | | 4 | 5 | 6 | 5 | 2 | 1 | 1 | .3 | | 3 | 2 | 1 | | 3 | 3 |
| Ehrenbergina undulata | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 20 | | | | | | | | | | | | | | | |
| Epistominella exigua | 5 | 14 | 18 | 2 | 15 | 18 | 6 | 20 | 8 | 17 | | 23 | 4 | 7 | | 4 | | .6 | 2 | 2 | | | | | | 4 | 7 | 2 | 6 | 15 | 11 | 11 | 9 | 2 | 12 | 8 | | | 4 | 12 | 9 | 15 | 7 | 6 | 12 | 8 | 1 | 7 | 8 | 13 | | 13 | 9 |
| E. umbonifera | | | | 5 | 46 | 37 | 23 | 3 | 24 | 22 | | 13 | 2 | | 2 | 20 | 48 | 57 | 57 | 64 | | | 100 | | 63 | 39 | 34 | 31 | 24 | 42 | 49 | 38 | | | | | | 1 | 4 | | 5 | 12 | 5 | 65 | 50 | 56 | 26 | 28 | | | | | 20 |
| Eponides polius | | | .8 | | | | .8 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| E. tumidulus | | | | | | | | | | | | | | | | 2 | 2 | | | | | | | | | | | 2 | | .7 | .5 | .8 | 1 | 3 | 3 | | | | 4 | | 2 | | 2 | | | | | | | 1 | | 1 | 2 |
| E. umbonatus and variants | 4 | 2 | .8 | 7 | 10 | 2 | 8 | 4 | 6 | | | 8 | 7 | | 3 | 4 | 6 | 1 | 5 | 4 | | 2 | | | | | 5 | 5 | 9 | 3 | 4 | 2 | 2 | 1 | 2 | 8 | 4 | | 7 | 7 | 2 | 4 | | 2 | 1 | 3 | 3 | 7 | 6 | 8 | 10 | 8 | 6 |
| Globobulimina cf. turgida | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Glomospira cf. gordialis | | .6 | | | | | .8 | | 3 | | | | | | | | | | | | | 5 | | | | | | 1 | 3 | | | | | | | | | | | | | | | | | | | | | 1 | | | 2 |
| Gyroidina lamarckiana | | | | | 1 | .6 | | 1 | | | | | | | | | | 2 | 2 | .6 | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | |
| G. orbicularis | | | 2 | 2 | | | | | | | | .8 | | 4 | | | | | | | | 2 | | | | | 1 | | | | | | | | | 2 | | | | 1 | 2 | 1 | | | | | | | .8 | | | 1 | |
| G. soldanii variants | 4 | 6 | 3 | | .4 | 2 | | 4 | 5 | 3 | | .8 | 4 | 4 | 7 | 4 | | | | | | 2 | | | | 2 | 5 | 2 | 4 | 2 | 1 | .8 | 1 | 4 | 2 | 6 | | 2 | 2 | 3 | 2 | .7 | 2 | | | | | | 2 | 3 | | 4 | 3 |
| Hoglundina elegans | 3 | 2 | 3 | | | | | 5 | | | | | | 2 | 3 | | | | | | | 5 | | | | | | | | | | | 12 | 10 | 2 | 2 | | | 2 | 5 | | | | | | | | | 6 | 27 | 2 | 4 | 1 |
| Lagenidae | | | .8 | 12 | 1 | | .8 | 2 | | 4 | | 2 | | 2 | 5 | 4 | 5 | .6 | 2 | 1 | | 2 | | | | 11 | 1 | 2 | 1 | 2 | | .8 | 1 | 2 | 2 | 6 | | | | | | | | .4 | | .7 | 1 | | 3 | | | | 3 |
| Laticarinina pauperata | | | 2 | | | | | | | | | | 2 | | 2 | 5 | | | | | | 2 | | | | | .7 | | | | | | | 1 | | 2 | | 1 | 4 | 1 | | | | | 1 | | | | 8 | | | 1 | |
| Miscellaneous arenaceous forms | 19 | 20 | 8 | 21 | 4 | 12 | 11 | 13 | 15 | 9 | 100 | 6 | 9 | 22 | 10 | 9 | 10 | 16 | 8 | 9 | | 5 | | | | 2 | 9 | 20 | 19 | 6 | 2 | 17 | 5 | 7 | 6 | 18 | 50 | 5 | | 5 | 2 | 9 | 24 | .4 | 4 | 2 | 2 | 24 | 8 | 4 | 19 | 1 | 22 |
| Miscellaneous Miliolidae | | | | | | | | | | | | | 2 | | | | | | | | | 5 | | | | | | | | | | | 5 | 4 | | | | 16 | | | | | | 1 | | | | | | | | | |
| Nonion barleeanum | 12 | .6 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 12 | 7 | 2 | | | | 2 | 1 | | | | | | | | | 6 | | 2 | 6 | |
| N. formosum | | | | | .4 | | .8 | | | 1 | | 3 | | | | 2 | 2 | | .8 | | | | | | | 2 | | 1 | | | 1 | 2 | | 1 | | | | | | | .5 | | | | | | | | 2 | | | | |
| N. germanicum | | 4 | 3 | 12 | | | 10 | 4 | 2 | | | 2 | 11 | 13 | | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | | |
| N. pompilioides | 3 | | | 5 | 1 | 1 | | | | 3 | | 5 | | | | | | | | 1 | | | | | | | | | | | .5 | | 2 | 2 | 2 | 2 | | | 2 | 1 | .5 | .7 | | .4 | | | 7 | | 6 | | 2 | | |
| Nummoloculina irregularis | | | | | | | | | | | | | | | | | | | | | | 15 | | | | | | | | | | | | | | | | 4 | | | | | | | | | | | | | | | |
| Ophthalmidium inconstans | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 7 | | | | | | | | | | | | | | | |
| Osangularia cultur | .6 | | .8 | | | | | | | | | | | | 5 | | | | | | | 3 | | | | | | | | | | | | | | | | 1 | 2 | | | | | | | | | | | | | | |
| Plectina apitularis | 3 | 2 | .8 | | .4 | .6 | | 1 | 2 | 4 | | | 2 | | | | 3 | 2 | 3 | | | 2 | | | | 2 | 1 | | | | | .8 | | | 2 | 2 | | | | | 5 | 2 | | | | | | | | | | | 1 |
| Planulina wuellerstorfi | 12 | 18 | 17 | 18 | 11 | 10 | 23 | 16 | 8 | 9 | | 10 | 13 | 15 | 12 | 9 | 6 | 10 | 13 | 10 | | 7 | | | 12 | 10 | 14 | 7 | 6 | 7 | 4 | 10 | 22 | 31 | 9 | 8 | 4 | 2 | 15 | 13 | 7 | 11 | 4 | 2 | 9 | 13 | 15 | 7 | 11 | 3 | 10 | 11 | 7 |
| Pullenia bulloides | 3 | 2 | 3 | 2 | 3 | 7 | 4 | 2 | 19 | 13 | | 16 | 13 | 4 | | 16 | 10 | 3 | 2 | 4 | | | | | 12 | 13 | 3 | 3 | 3 | 4 | 7 | 2 | 2 | 1 | 3 | 2 | 4 | | 4 | 1 | 4 | 4 | 2 | 6 | 6 | 5 | 9 | | 5 | 9 | 2 | 3 | 10 |
| P. quinqueloba | 1 | 6 | 2 | 2 | 1 | 1 | 2 | 5 | 3 | 1 | | | | 7 | 3 | 7 | 2 | | | | | | | | 12 | 2 | 1 | 2 | | | .5 | .8 | | 1 | | | | | 9 | 4 | 2 | 1 | 2 | 3 | 5 | 3 | 4 | 3 | 3 | 5 | | 6 | |
| P. cf. riveroi | | | | | | | | | | | | | | | | | | | | | | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| P. sp. | | | | | | | | | | | | | | | | | | 1 | .8 | 2 | | 2 | | | | | 1 | | | 2 | 1 | | | | | | | | | | 1 | | 2 | | | .7 | | | | 1 | | | |
| Pyrgo murrhina | 5 | 4 | 3 | | | 2 | 2 | 2 | | | | | | 2 | 7 | | | 2 | | .6 | | | | | | | 1 | | 1 | 4 | | | | | 5 | | | | 2 | | | | | .4 | | 1 | | 3 | 3 | 4 | 2 | 4 | 1 |
| P. oblonga | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .7 | | | | | | | | 1 | | | |
| Quinqueloculina venusta | | | 3 | | | .6 | 3 | 2 | 2 | | | | | 2 | 3 | | | | | | | | | | | | 1 | 1 | | .7 | 1 | .8 | 7 | 5 | 9 | 2 | | | | 4 | .5 | | | | | | | | .8 | | 6 | 1 | |
| Q. cf. weaveri | | | 3 | | | | | | | 1 | | .8 | 2 | 2 | 12 | | | .6 | | | | 5 | | | | 2 | | 1 | 3 | | | | | | | | | | | 1 | 2 | | | | | 1 | | | | 1 | | 1 | 2 |
| Robertina bradyi | | | | | | | | | | | | | | | 2 | | | | | | | 2 | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | |
| Rotamorphina laevigata | 2 | 2 | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Sigmoilina schlumbergeri | .6 | 3 | 6 | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | 7 | 4 | 8 | | | | | | | | | | | | | | | 14 | 6 | | |
| S. tenuis | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .5 | .7 | | | | | | | | | | | |
| Siphotextularia curta | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| S. rolshauseni | | | 2 | | | .6 | | | | | | | 2 | | 2 | | | | .8 | | | | | | | | | | | | .5 | | 2 | | | | | | 2 | 1 | .5 | | 1 | 1 | | .3 | | | .8 | | | | |
| Spiroloculina sp. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .5 | | | 1 | 2 | | | | | 1 | .5 | | | | | | | | | 3 | | | |
| Textularia australis | | | | | | | | | | 1 | | | | | | | 2 | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | 3 | 6 | 2 | | | | | | | | | | |
| Tretomphalus atlanticus | | | | | | | | | | | | | | | | | | | | | | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Triloculina tricarinata | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | .8 | | 2 | | |
| Uvigerina auberiana and vars | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| U. hollicki | 12 | 2 | .8 | | | | | 1 | | | | | 4 | | | | | | | | | 5 | | | | | .7 | 1 | | | | | | | | | | 4 | 2 | | | | | | | | | | 6 | | 10 | | |
| Valvulineria humilis | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 7 | 5 | | | | | | | | | 1 | 9 | 3 | 17 | 21 | 42 | 10 | 2 | 4 | 20 | 17 | | | | | |
| Virgulina advena | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | .5 | | | | | | | | | | | | | | | | | | 2 | | | | |
| V. bradyi | .6 | .6 | | | .4 | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | |
| V. complanata | .6 | | | | | | | | | | | | | | | | | | .8 | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | |

### *Interpretation of Core Faunas*

*Recognition of faunal sequences.* Interpretations of the vertical sequence of the faunas in the long cores are summarized in Figures 22 to 26. The faunal changes shown by the modern type assemblages are all based upon what is known of the distribution of the modern planktonic species. New information on these distributions is summarized on Figures 3 to 19 and is described in a previous section.

The criteria used in interpreting the vertical sequences depend upon whether a core was collected from mid- or low latitude. The following cores are from mid-latitude locations and are expected to contain the normal mid-latitude faunas for their locations: 215—223, 276—296. The remainder of the cores are relatively low-latitude in position and contain a typical low-latitude fauna.

Faunal variations in the mid-latitude cores are shifts to faunas which appear to be characteristic of somewhat higher latitudes. Recognition of this higher-latitude assemblage is based largely upon the decrease in percentage of *Globorotalia truncatulinoides* and increase in percentage of *Globigerina pachyderma.* Other criteria which seem to be of significance in some samples is the disappearance of the *Globorotalia menardii-tumida* group and *Pulleniatina obliquiloculata,* slight decrease in percentage of *Globigerina inflata* and *Globigerinoides sacculifera,* and increased frequency of *Globigerina bulloides.* These latter criteria do not seem to apply in many cores.

In the low-latitude cores the recognition of a mid-latitude fauna is based largely upon the decrease in frequency of *Globorotalia menardii-tumida* and *Pulleniatina obliquiloculata* and the presence or marked increase of *Globigerina inflata* and/or *Globorotalia truncatulinoides. Globigerina bulloides, G. pachyderma,* and *Globorotalia scitula* also may be present in the mid-latitude faunas identified from the low-latitude cores.

It does not appear feasible to attempt to establish more definite, numerical criteria f
recognizing these mid- and low-latitude faun
in the cores. Our knowledge of the distributi
of the modern faunas present in surfa
sediment samples is very inadequate; als
there is relatively little information on t
distribution of living planktonic Foraminife
from plankton hauls. Data from plankton hau
given by Schott (1935) and Phleger (195
demonstrate that while planktonic speci
are more abundant in the surface 100 m.
water, they also live in significant abundan
at much greater depths. The significance
the distribution at depth in terms of temperature adjustments is uncertain. Moreove
Phleger (1951) reports a few living plankton
forms living on or near the bottom fro
the northwestern Gulf of Mexico. Recentl
numerous living planktonic specimens hav
been identified from undisturbed bottom samples collected from the northeastern Gulf
Mexico. In addition, real knowledge of th
ecologic factors which affect the distributio
of planktonic Foraminifera is lacking. Conclusions based upon distribution data are onl
partially reliable and should be supplemente
by physiological experiments if we are to hav
a real understanding of the significance of cor
distributions.

*Mixed planktonic faunas.* A few cores contai
assemblages which appear to be mixed planktonic faunas, with relatively high percentage
of both low- and mid-latitude species. Thes
mixed faunas are tentatively identified fro
the following: in Core 233, at 390 cm. and 93
cm.; Core 234, at 130 cm., 190 cm., and 98
cm.; Core 236 contains three layers of apparentl
mixed faunas below 700 cm.; Core 239 at 4 cm.
in Core 242 all samples containing mid-latitud
assemblages appear to be mixed faunas.

The positions of all these cores containin
mixed faunas are approximately betwee
0°—7° N Lat. and 18°—25° W. Long. Thi
is off the coast of Africa, south of Cape Verde

is suggested that the modern mixed plank- nic assemblage described in a previous ction is the result of the convergence of tropi- l and mid-latitude waters containing different semblages of planktonic Foraminifera. The esent convergence area is located at approxi- ately 20°—25° N Lat., also off the coast of rica, but north of Cape Verde. These data rongly suggest that at some times during the st the convergence area has shifted southward least 10° or 15° of Latitude. If this suggest- interpretation is correct, then the position the North Equatorial Current and also e Trade Winds belt may also have shifted uthward by this amount at some times uring the past.

*Displaced faunas.* There are several bentho- c faunas in the present cores which contain ecies at present characteristic of shoaler ater than the depths at which they were llected in the cores. Some of these assemblages e mixed with the normal deep-water benthonic ecies and some are relatively pure shallow- ater assemblages. The displaced bentho- c faunas are found in the following Cores: 5, 217, 221, 228, 248, 252, 257, 258, 262, nd 267. These displaced faunas are located the following areas: the displacement in ore 215 near the Canary Islands; Cores 1 and 228 near the Cape Verde Islands; ores 248, 252, 257, 258 and 262 in a ne parallel to the coast and about 300 to 0 miles off the coast of South America, om 2° N. Lat. to off the Orinoco River; ore 267 near Puerto Rico in the West dies. The striking fact about the positions all these cores is that they are relatively ear areas of considerable submarine relief. one of the cores collected at great distances om areas of high relief contains the shallow- ater, mixed benthonic assemblage.

The layers in the cores containing displaced enthonic faunas vary considerably in thick- ess. Core 221, from near the Cape Verde Islands, contains a mixed deep and shallow-water benthonic assemblage in most of the samples throughout its 560 cm. of length. Core 228, from near the Cape Verde Islands, also is believed to contain much displaced material throughout its 430 cm. Core 252, from off South America, appears to contain two separate displaced layers each of which is approximately 200 cm. in thickness, separated by a layer showing no evidence of displacement. Core 257, from off the Amazon River, contains a section of displaced material in the bottom of the core greater than 400 cm. in thickness. Core 258, also from off the Amazon River, contains 175 cm. of displaced material at the bottom of the core, and in addition at least two thin layers of displaced material at higher levels. In Core 262 a thin layer containing displaced Foraminifera is present only in the bottom sample at 1279.5—1280 cm. Core 267, from the West Indies region, is composed of *Globigerina* ooze and contains displaced materials throughout its entire 1180 cm.

Most of the core sections containing displaced benthonic species also contain abundant sediment of sand sizes. Core 221 is one of the more striking examples. The top 115 cm. is essentially sand and below that depth there are numerous thin sand layers and lenses. The sand is composed of relatively large quartz grains some of which are rounded and polished. There are abundant mollusc shell fragments in several places, many of which are well-rounded, and rugose ostracods are recorded from some samples. In Core 228 there is abundant fine sand, some in layers, and much mixed with mud. The thick displaced layer in Core 257 contains a series of relatively thin layers of sand and mud. In Core 267 no evidence of sand was seen in 120 thin samples examined; the entire core is a *Globigerina* ooze.

The presence of shallow-water benthonic Foraminifera in sediments collected from deep water seems to be valid proof of displacement of the specimens and either part or all of the enclosing sediment from shallow water. The presence of normal deep-water benthonic species along with the shallow-water types or enclosing pure layers of them is additional proof. Submarine turbidity currents have been widely discussed in recent years by Kuenen (1951), Menard and Ludwick (1951), Shepard (1951), Ericson *et al* (1952), and others. Phleger (1951 a) has discussed the presence of displaced faunas from various parts of the world, and has suggested slightly different mechanisms for emplacement of different kinds of assemblages.

It is not the purpose of this paper to discuss the possible mechanisms of movement of this sediment which has been displaced downslope. A few generalizations can be made, however, on the data already presented. Presence of displaced layers of thicknesses ranging from only a few millimeters to a few meters, suggests that there may be considerable variation in the amount of displaced material and/or the distance which it was displaced. A series of displaced layers in the same core indicates that displacement may occur at numerous different times at the same place and over a long period of time. The occurrence of thick displaced layers off South America at least 300 miles from the nearest known source indicates that large amounts of material may move for considerable distances. In addition, displaced sand in deep water is only to be expected relatively near areas of considerable submarine relief.

*Fossil faunas.* Four fossil planktonic species and one fossil benthonic species are recorded from the cores, as follows:

*Globigerina altispira*
*G. venezuelana*
*Globorotalia* sp. 2
*Sphaeroidinella rutschi*
*Cassidulina reflexa*

In addition, there are two previously und scribed benthonic species associated with th known fossil forms: *Bolivina* sp. 2 and *Bul* *minella* sp. These species occur only in Co 233. They are not referred to in the co description. *Globorotalia* sp. 2, although und scribed also, is included since it is found mo frequently and shows an interesting distrib tion. It has been observed in a Bowden Ma sample from Jamaica.

*Globorotalia multicamerata* has not bee included in the above lists but is found assoc ated with or slightly above the other foss forms in the cores. It has been reporte only from the Miocene with the exception one report from the Recent near Cuba b Cushman and Bermudez (1949, p. 30). I is suggested that this occurrence may be du to reworking or contamination.

The previously reported occurrences of th fossil species in the general West India Caribbean region are given in the specie discussions above. The suggested age of th benthonic species is from the upper Middl Miocene since two of the species, *Buliminell* sp. and *Cassidulina reflexa* are found in ma terial from Haiti of this age. This is furthe corroborated by the evidence of the planktoni species which show an overall range from Middl Oligocene through Middle Miocene althoug some species extend above or below these limit

One or more of these fossil species occu in four of the present cores. Core 234 contain the following forms which appear at or some what above 1119.5 cm.: *Globigerina altispir* *G. venezuelana*, *Globorotalia multicamerata*, an *Spaeroidinella rutschi*. *Globorotalia* sp. 2 appe ars at 1019.5 cm. In Core 238 fossils appea as follows:

*Cassidulina reflexa*: 1030—1084 cm.
*Globigerina altispira*: 1090 cm. to botto
*G. venezuelana*: 1090 cm. to bottom

There is no faunal evidence for displaceme in either Core 234 or 238. The Miocene mat l in Core 234 is more compact, and it appears obable that there is a disconformity be- een the Miocene and younger sediment. ere is no evidence for such a disconformity Core 238, and it seems possible that it presents more or less continuous deposition. l the modern planktonic species, except *loborotalia tumida*, occur with the middle ertiary assemblage and evidently have a nge back to the Miocene. There is a possi- lity that *Globorotalia multicamerata* and *G.* . 2 may have a somewhat higher geologic nge than the other fossil species, since they sually occur higher in the cores.

In Core 233 the following fossil species ccur in three samples below 800 cm.: *Globige- na altispira, G. venezuelana, Globorotalia mul- camerata, G.* sp. 2, *Bolivina* sp. 2, *Bulimi- ella* sp. and *Cassidulina reflexa*. This assem- lage suggests a Middle Miocene age. There a possibility that this lower section contains worked Miocene fossils since they occur only 801—802 cm. and at 1248—1300 cm., or e entire lower section may be of Miocene age.

The above three cores are found in a north- est-southeast line paralleling the coast of frica and are placed between 0° and 7° N at. They bear no common relationship to nderwater topography but do bear roughly e same relationship to the coast of frica.

*Globigerina altispira* and *G. venezuelana* occur elow 610 cm. in Core 267 and *Globorotalia* . 2 occurs in a few samples from 90 cm. the bottom of the core. This core is shown contain evidence of displacement for the ntire core (see p. 00). The fossil planktonic rms may have been displaced from a shoaler epth or they may have been deposited in lace. The sequence of the fossils and dis- laced species suggests that displacement was king place during the late Miocene, and ossibly Pliocene.

The middle Tertiary sections in these cores veal some interesting facts not shown in previous stratigraphic studies. These consist of the downward range of several planktonic species not hitherto known below the Pliocene. The deep-ocean nature of these deposits may explain this extension since previous stratigraphic work is based on relatively few deep-sea deposits. The ranges of these species have been obtained from the study of papers by Grimsdale (1952) and others. The species include *Candeina nitida*, *Globigerina eggeri*, *Globorotalia hirsuta*, and *G. punctulata*. The last species has not been reported below the Recent, but may have been listed under other names although not apparently so in the West Indian-Caribbean region. Although *Globigerina eggeri* is not reported in the Miocene it is possible that Miocene reports of *G. dubia* refer to this species. These above occurrences are exclusive of Core 267 which shows displacement. The benthonic species, aside from the known fossil forms, appear to range throughout the cores showing fossil sections and have not been analyzed due to the scarcity of information on the ranges of many of the species.

*Correlation of faunas.* Correlation of post-Miocene, and particularly post-Pliocene planktonic Foraminifera faunas between deep-sea cores is difficult and may not be possible. The species are modern ones and although minor variations having age significance may be established with further, detailed study, there are no presently recognized extinct species or varieties in this age range. *Globorotalia tumida* (*sensu strictu*) appears to be useful in having a lower limit of range, but this species does not occur in all cores. The only apparent general means of correlation of these microfaunas is by matching supposed similar events based upon faunal interpretations. It can be inferred, for example, that the uppermost »colder-than-modern» fauna in all the cores are correlatives. Likewise, successively lower »warm» and »cold» water

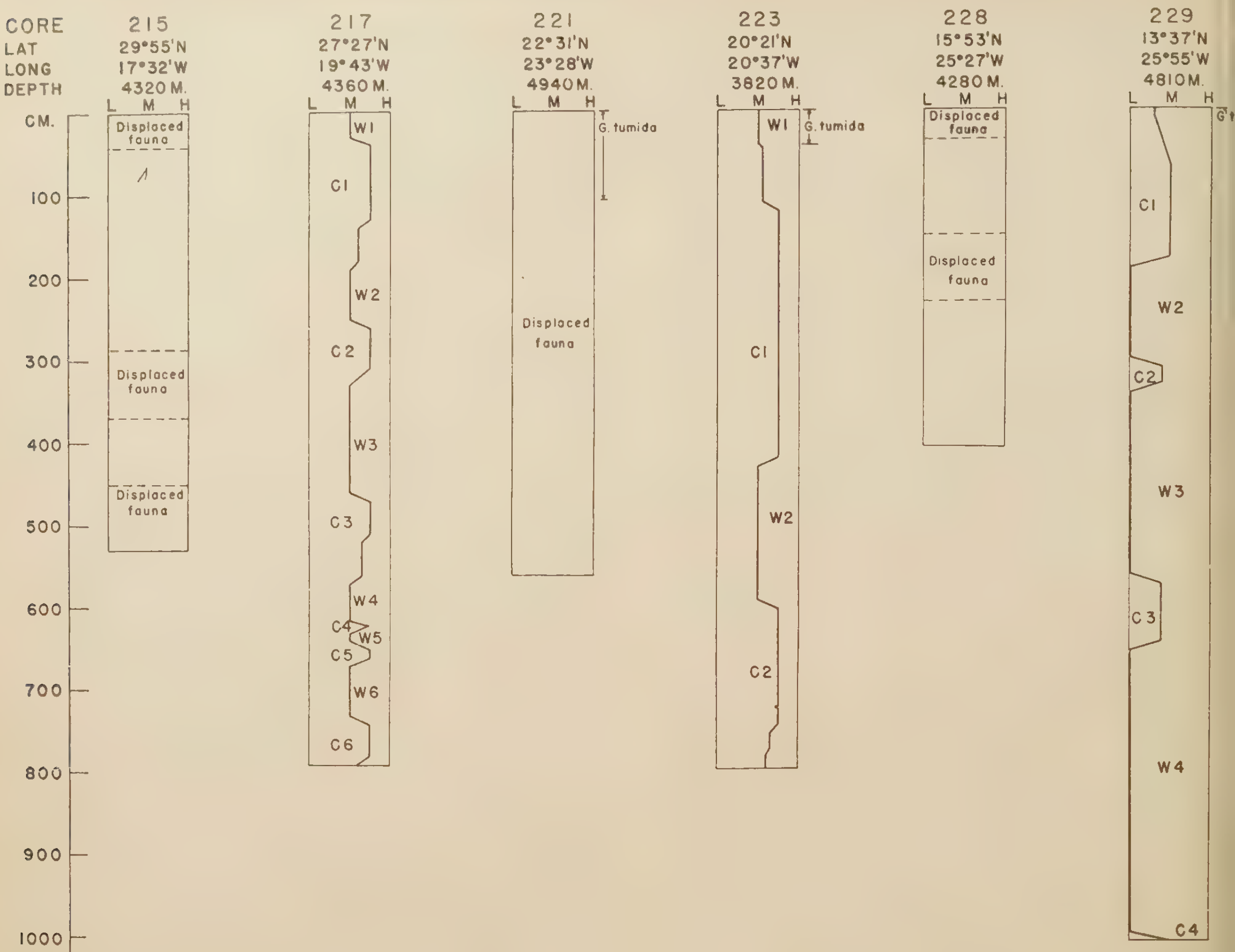
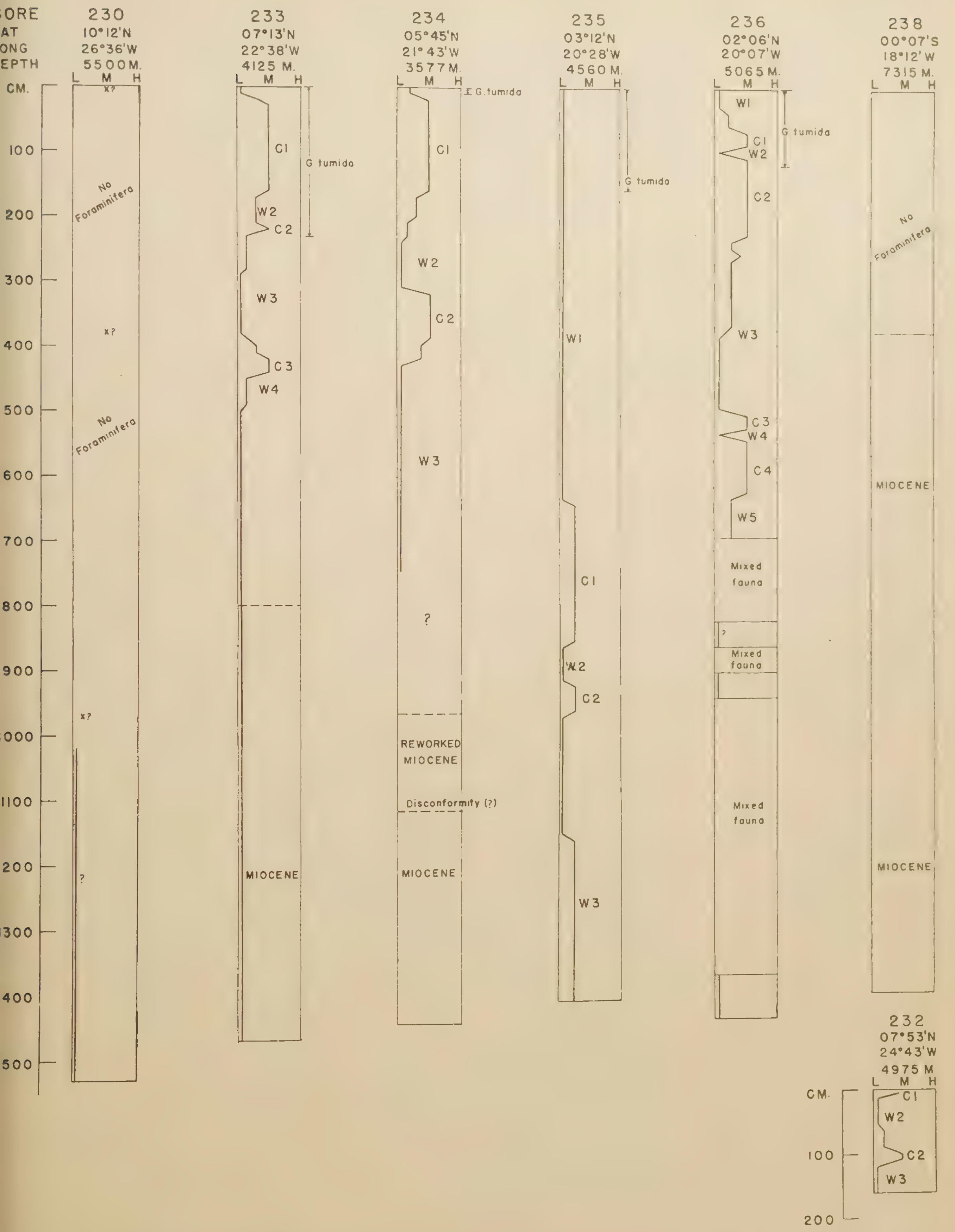

CORE
LAT
LONG
DEPTH
CM.
215
29°55'N
17°32'W
4320 M.
217
27°27'N
19°43'W
4360 M.
221
22°31'N
23°28'W
4940 M.
223
20°21'N
20°37'W
3820 M.
228
15°53'N
25°27'W
4280 M.
229
13°37'N
25°55'W
4810 M.
L M H
Displaced fauna
G. tumida
W1
C1
W2
C2
W3
C3
W4
C4
W5
C5
W6
C6
100
200
300
400
500
600
700
800
900
1000

Fig. 22. Interpretations of Foraminifera faunas in Cores 215, 217, 221, 223, 228 and 229. L, low-latitude faun M, mid-latitude fauna; H, high-latitude fauna. C, colder-than-present; W, warm-as-present.

faunas in the various cores can be interpreted as having been deposited at the same time. Correlation is based, therefore, on matching a series of events which in turn are based on ecological interpretations of the microfaunas.

Interpretations of the faunas in the cores, shown in Figures 22 to 26, are based entirely on the planktonic assemblages, as discussed above. Where a lower planktonic fauna in any core is different from the modern one in the same core and like the modern fauna in a higher latitude it is interpreted as representing colder oceanic surface waters. Such a fauna is given the designation »C» on the diagrams in Figures 22 to 26, indicating that it is interpreted as a »colder-than-modern» fauna. Faunas more or less like the modern one at the place where a core was collected are indicated by »W» in the core diagrams to signify approximately »war as-modern» surface oceanic water at that plac The modern fauna in any core is labelled »W the uppermost »colder» fauna is labelled »C and successively lower »cold» and »warm» faun are given successively larger numbers where t sequence appears to be unbroken by displac ment of faunas.

The faunal variations in a core may be qui real but their significance can be questione The differences between low-, mid-, and hig latitude faunas have been correlated with t distribution of oceanic surface isotherms. Th correlation is imperfect and is based upon fe and relatively unreliable data. It is assum that surface-water temperatures are of prima ecologic importance, and this is not necessar true, as discussed above. It is possible th



23. Interpretations of Foraminifera faunas in Cores 230, 232, 233, 234, 235 and 236. L, low-latitude fauna; M, mid-latitude fauna; H, high-latitude fauna. C, colder-than-present; W, warm-as-present.

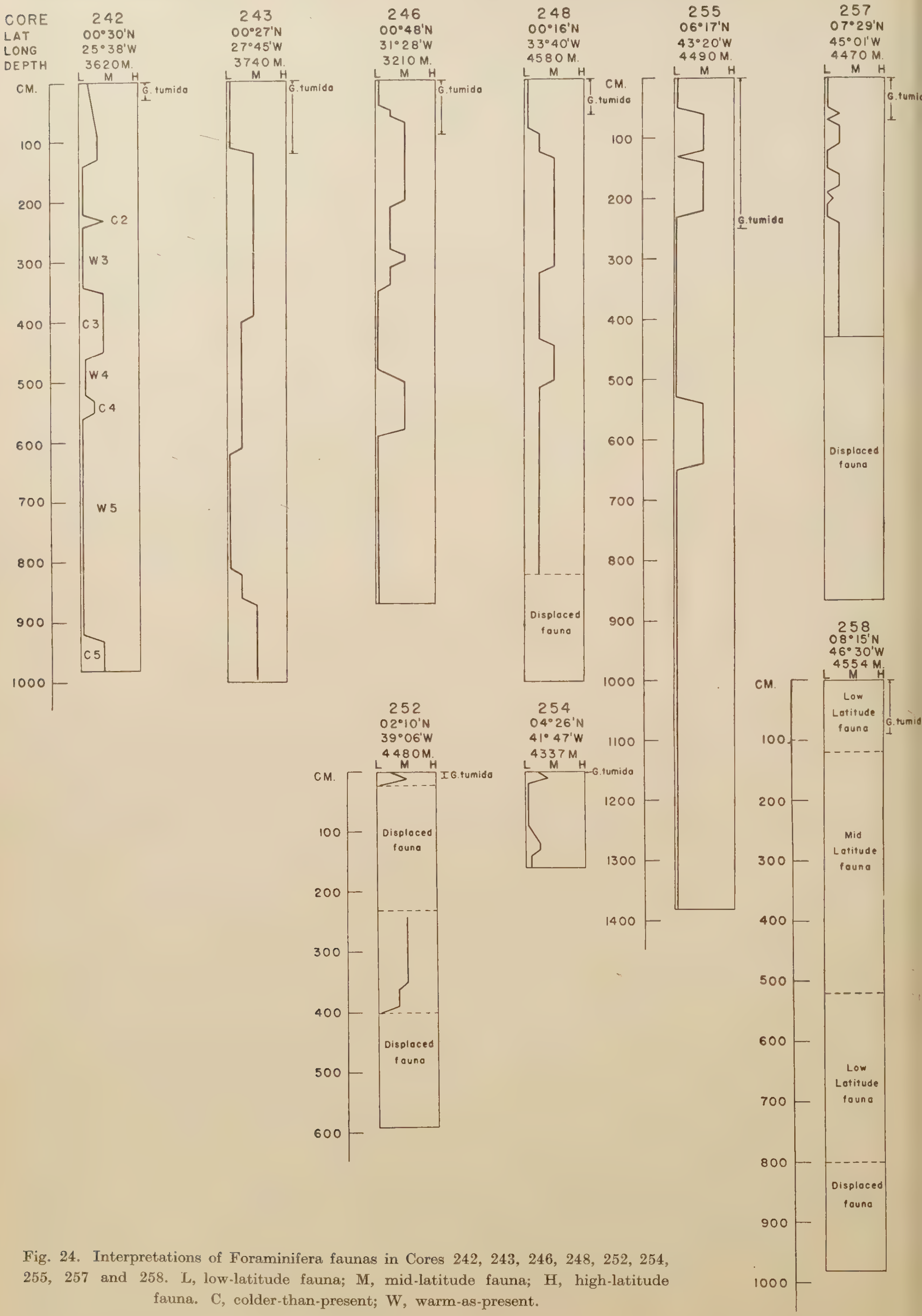
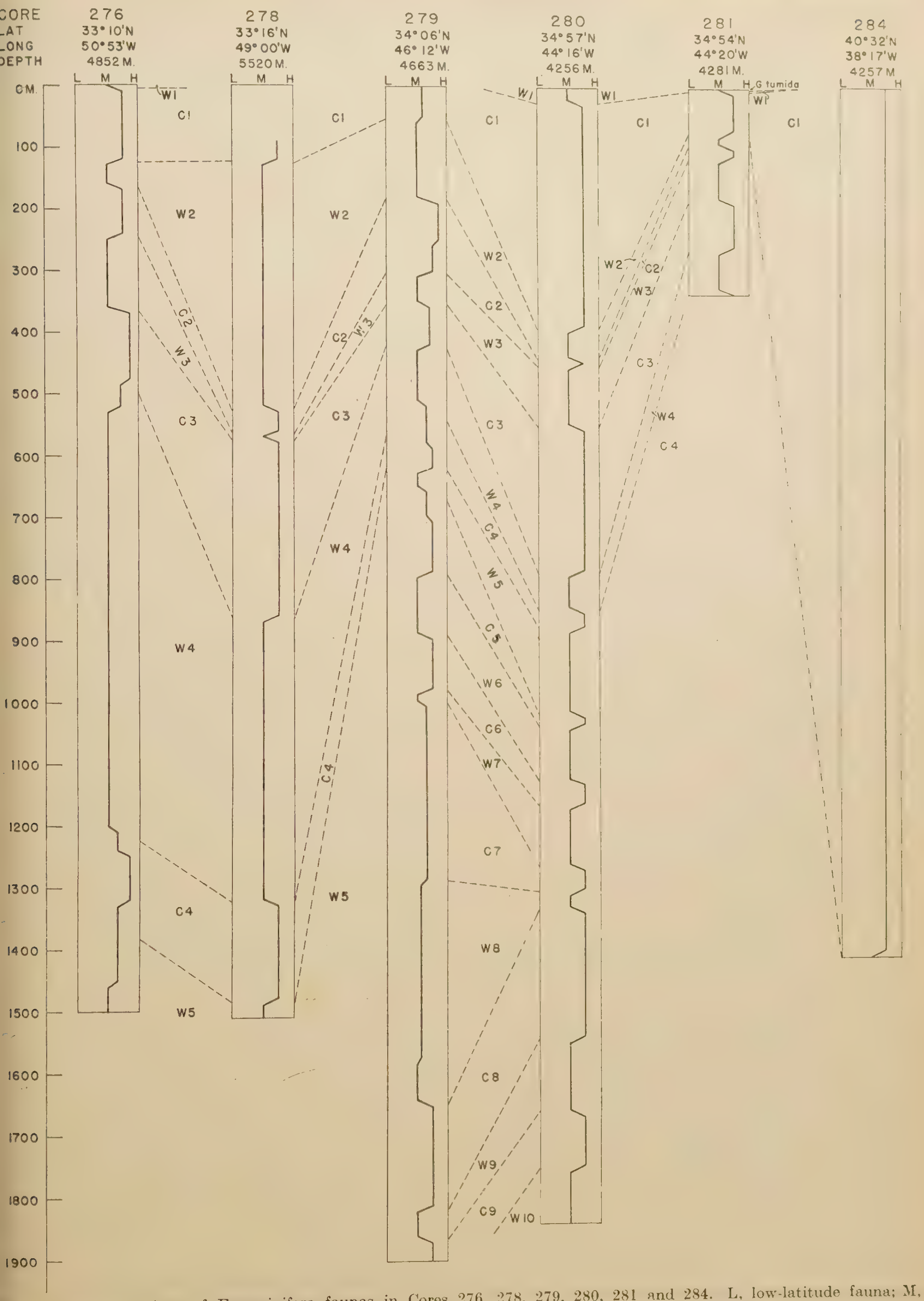


Fig. 24. Interpretations of Foraminifera faunas in Cores 242, 243, 246, 248, 252, 254, 255, 257 and 258. L, low-latitude fauna; M, mid-latitude fauna; H, high-latitude fauna. C, colder-than-present; W, warm-as-present.


CORE
LAT
LONG
DEPTH
276
33°10'N
50°53'W
4852 M.
278
33°16'N
49°00'W
5520 M.
279
34°06'N
46°12'W
4663 M.
280
34°57'N
44°16'W
4256 M.
281
34°54'N
44°20'W
4281 M.
284
40°32'N
38°17'W
4257 M
L M H
CM.
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
G tumida
W1
W1?
C1
W2
C2
W3
C3
W4
C4
W5
C5
W6
C6
W7
C7
W8
C8
W9
C9
W10

ig. 25. Interpretations of Foraminifera faunas in Cores 276, 278, 279, 280, 281 and 284. L, low-latitude fauna; M, mid-latitude fauna; H, high-latitude fauna. C, colder-than-present; W, warm-as-present.

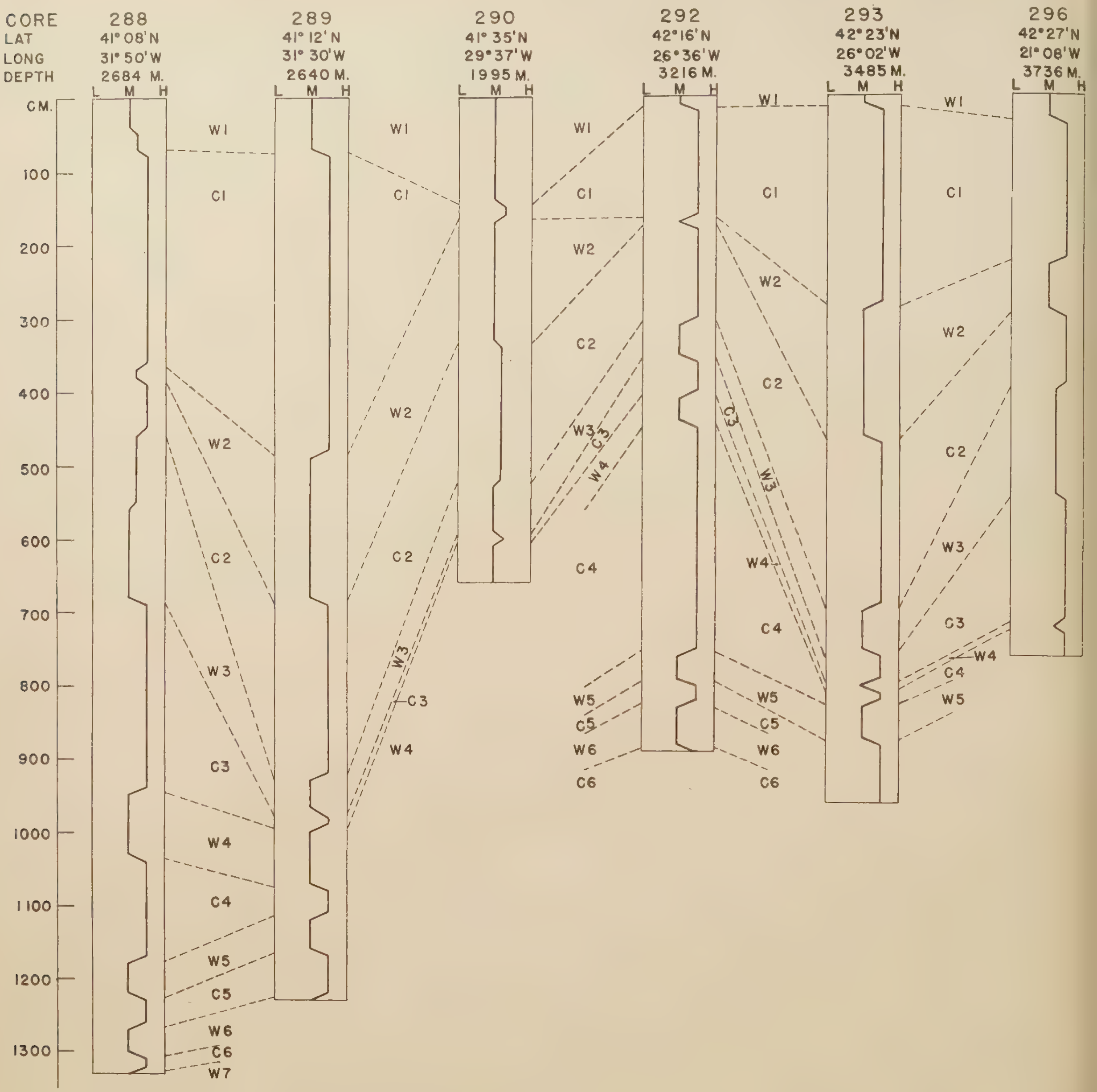


Fig. 26. Interpretations of Foraminifera faunas in Cores 288, 289, 290, 292, 293 and 296. L, low-latitude fauna; M, mid-latitude fauna; H, high-latitude fauna. C, colder-than-present; W, warm-as-present.

some of the faunal variations may be caused by local water mass migrations which are not necessarily of very great over-all significance.

The only series of cores for which we believe there is a good possibility of correlation are those taken in the mid-latitudes in the mid-North Atlantic, between approximately 32° N. Lat. and 42° N. Lat. These cores are the following: 276, 279, 280, 281, 284, 288, 289, 290, 292, 293 and 296. Dashed correlation lines have been drawn between layers where correlation is suggested (Figures 25, 26). It should be emphasized that these correlations are speculative and are to be considered with the qualifications mentioned. It does not seem desirable to attempt to further assign age names to them based upon North American or European Pleistocene chronology.

No attempt is made here to speculate upon the correlation between cores in mid and low latitudes. The »warm» and »cold» faunas are numbered in order, beginning at the top of each ore. It is not intended that these numbers ecessarily imply correlation, especially beween mid- and low-latitude cores, but it is at east possible that such correlation does exist.

The range of *Globorotalia tumida* (*sensu trictu*) may be of some value in correlation of hese cores. This species occurs in the modern auna and for varying depths below the surface ediment. It appears to extend back only to he last higher latitude fauna (Cl) in all cores vhere it occurs, with one possible exception. t may be inferred, therefore, that this species s confined to latest glacial and post-glacial imes, if we interpret the uppermost higheratitude fauna as late glacial in age. In general his species is confined to the lower-latitude ores.

## Observations on Solution of Calcium Carbonate

Numerous samples from the cores contain a igh percentage of broken tests of Foraminifera. ome samples contain essentially no broken ests, others consist only of fragments, and still thers contain no evidence of Foraminifera or nly a few fragments. Only essentially complete pecimens were counted for the faunal list on 'ables 2 to 37; the samples having a high opulation are those with few broken tests and hose with low populations generally have a igh percentage of broken tests.

Abundant observations of these core faunas eem to indicate that this breakage is fundaientally due to solution of the calcium carboate causing weakening of the tests and that iechanical causes are secondary. All stages of olution of the calcareous tests have been bserved in examination of several hundred iousand specimens in the course of this study. olution may be well illustrated by the speciiens of *Globorotalia menardii-tumida* shown on 'late 12. The figures on this plate show rogressive stages of solution observed in ifferent specimens of this species. These specimens are typical of the solution effects observed in *G. menardii-tumida* and are duplicated in several hundred samples, although all solution stages shown are not necessarily seen in every sample where solution has occurred.

Some planktonic Foraminifera species appear to be dissolved more readily than others. Many or most of the *Globigerina* species appear to be attacked before the *Globorotalia* species; *Pulleniatina obliquiloculata* seems to be the last to be destroyed. Many samples contain only pieces of the thick keels of *Globorotalia menardii-tumida* and a few complete specimens of *Pulleniatina obliquiloculata*. It is quite obvious that a fauna containing these two species would have had a large population and consist of several planktonic species. This apparent difference in rate of solution probably is due to the structure of the test wall. The test of most species of *Globigerina* appears to be more porous than that of *Pulleniatina*, for example, and the thickened keel of *Globorotalia menardii-tumida* is the most massive part of this test. Partial solution of *Globigerina* specimens causes them to be more fragile than fresh specimens and thus more easily broken.

The benthonic species observed in the cores were for the most part unbroken and showed no signs of solution. It is possible that their tests are contructed to resist solution in their natural environment — an environment which is alien to the planktonic species.

Observations have been made on solution effects in the surface faunas from the short cores. There is wide variation from no evidence of solution to essentially complete solution of the fauna. In general, the samples from shallower depths show little solution effect and those from depths greater than approximately 5,000 m. show intensive solution, but there are some rather striking exceptions. Samples 242, 243 and 246 from 3,210 to 3,740 m. contain fresh faunas as also do samples 288 from 2,684 m., and 292 from 3,216 m. Samples 224, from 2,810 m. and 225, from 2,973 m., on the other hand, contain 30—40 % of broken specimens attributed to solution. Samples 247 from 4,285 m. and 257 from 4,470 m. show little solution effect, whereas, in sample 252 from 4,480 m. approximately 90 % of the specimens are broken and there is abundant evidence of solution. Sample 283 from 4,940 m. has only a small amount of solution, but sample 261 from 5,128 m. has approximately 95 % broken material and a very low population of complete specimens. Sample 238 from 7,315 m. contains about ten rather fresh specimens of Foraminifera; this suggests that these specimens may have been deposited just previous to the collection. Sample 240 from 7,500 m. contains at least 50 % broken specimens but there is a relatively large population of whole specimens. Sample 271 from 6,310 m., on the other hand, contains no Foraminifera and it may be assumed that the fauna has been completely destroyed. Observations on these samples are cited as examples only; further data are on file at the Marine Foraminifera Laboratory.

One of the striking features of the cores is the presence of layers showing little evidence of solution and others showing intensive solution in the same core. Observations on the relative amount of breakage, and thus solution of the tests, have not been made on all the cores, but the following examples will illustrate this differential layering. In Core 230, from a depth of 5,500 m., 90 % or more of the Foraminifera are broken, except between approximately 1,450 and 1,500 cm. where the material is relatively fresh with only approximately 10 % broken specimens. Core 233 from 4,125 m., 234 from 3,577 m., 235 from 4,560 m., and Core 236 from 5,065 m. all have layers which appear to have been subjected to intensive solution alternating with relatively fresh layers. In Core 238, from 7,315 m., sample 74 contains only about 10 % of broken specimens of a large fauna although most of the Foraminifera in other samples from this core appear to have been destroyed. Likewise, Core 239 from 7,490 m. contains little evidence of solution i the top sample and abundant evidence in othe sections of the core.

These observations of solution effects are no quantitative since there is no method obviou to the writers of estimating the amount o calcium carbonate that has been dissolved fro the samples. In addition to solution breaks pitting, and holes, apparent redeposition o calcium carbonate is observed on numerou specimens and some individual calcite crystal are believed to be of secondary origin. It i difficult to explain the observations of solutio of calcareous Foraminifera from the dee Atlantic sediments. Most of the faunas fro deeper water show abundant evidence of solu tion, but some are relatively fresh; conversely some samples from shoaler stations have marke evidence of solution. The abundance or paucit of solution of calcium carbonate may be in par related to the rate of production of the *Globi gerina* fauna and thus the rate of supply o calcareous material to the sediment. Where th rate of supply of calcareous tests to the sedimen is high, the bottom water may become satu rated with calcium carbonate and lose much o its ability to dissolve additional material. A low rate of supply of calcareous tests to th sediment, on the other hand, may have littl effect on the calcium carbonate saturation o the bottom water and the solution effect o the Foraminifera population may be marked

Areal variations in the amount of solutio may be caused by a local lowering of the p of the bottom water. It is also possible tha different water masses have slightly differen saturations of calcium carbonate. If thes differences exist in the deep bottom wate however slight, the result may be marke geographic variation in calcium carbonat solution. The presence of alternating laye showing evidence of intensive solution an layers of fresh calcareous tests suggests tha some may occur after burial of the sedimen If post-depositional solution occurs, it must b lective because the intensity has been different different layers. It appears more probable, owever, that the different layers essentially cord the intensity of solution which occurred ; or near the sediment-water interface at some rlier time.

## Summary Discussion

All the cores studied contain one or several gher-latitude faunas, separated by faunas ormal for the latitude, according to our terpretations. It may be assumed that these gher-latitude faunas were deposited during time of lower sea surface temperatures than ose now existing at the position of any core. he colder faunas from Atlantic cores have een interpreted as approximate correlatives the Pleistocene glacial stages of Europe and orth America by Schott (1935), Bramlette d Bradley (1940), Phleger (1939, 1942, 1951) d Phleger and Hamilton (1946). The areas vered by previous studies include the low-titude areas between Brazil and Africa, the orthwestern Gulf of Mexico, the continental ope of the western North Atlantic, and the osition of the cable crossing between New-undland and Ireland. This is a widespread istribution in the North Atlantic and covers any of the principal areas, although the ensity of sampling is low and numeros im-ortant areas are not covered. None of the ores reported by previous authors exceeds bout three meters in length and most are nsiderably shorter.

It appears quite possible that the uppermost gher-latitude faunas in the Swedish Deep a Expedition cores represent times of cooler rface water during a Pleistocene glacial age. It is possible that some of the lower old» and »warm» faunas extend into the iocene. The composition of the Miocene unas is generally a modern low-latitude type; e cores containing this fauna are in low titudes and it can be assumed that late Miocene conditions were essentially similar to those at present existing.

The »colder» faunas in the low-latitude cores are like our modern mid-latitude faunas, and this suggests that surface temperature conditions were like those now obtaining in mid-latitudes. The mid-latitude »colder» faunas are like those in higher latitudes, suggesting that surface temperature conditions were like those now prevailing north of 43° N Lat. and probably north of about 50° N Lat. This suggests that during the stages cooler than present there was a southward shift of the isotherms. If we assume that the higher-latitude faunas are to be correlated between mid and low latitudes, a general southward shift of the isotherms for the entire North Atlantic is indicated. Since the higher-latitude faunas in the low latitude cores suggest cooler surface temperatures than present ones on those latitudes, it may be concluded that modern tropical sea surface temperatures did not exist in the North Atlantic at times when these faunas were deposited. These data indicate, therefore, a general southward migration of sea surface isotherms during the »cooler» stages and a general lowering of surface temperature in the North Atlantic even in tropical areas. It should be emphasized that these conclusions are speculative and are based on the premises: 1) that the higher-latitude faunas were deposited during times of lower sea surface temperatures, and 2) that the higher-latitude faunas are to be correlated between cores.

The recognition of pre-modern, apparently mixed mid- and low-latitude planktonic faunas from some cores is interesting in this connection. The modern mixed assemblage occurs at the approximate position of the convergence of the Equatorial Counter Current and the Canaries Current water to form the North Equatorial Current, at 15° to 20° N. Lat. off the coast of Africa. The lower mixed corefaunas occur in cores which were collected between approximately 0° and 7° N. Lat., also off the coast of Africa. These faunas suggest that at the time they were deposited the convergence had moved southward through at least 10° of latitude. It can be assumed that the Trade Winds, or their equivalent, also had shifted southward to an approximately equatorial position. The implications of this are uncertain. It may suggest that the northern hemisphere mid and low-latitude wind belts were displaced toward the southern hemisphere, or it may indicate a telescoping of the wind circulation in equatorial regions. The effect of such a modification of the wind system would be expected to have far-reaching effects on the Atlantic water circulation and therefore far-reaching effects on continental climates.

The widespread occurrence of displaced faunas may be of considerable importance to the deposition of sediment in the North Atlantic. As indicated above, the displaced faunas appear to be located near areas of considerable relief. Data from these cores and from elsewhere (Phleger, 1951) suggest that displaced faunas cover only a small percentage of an ocean basin, even though they may have considerable areal extent. It appears reasonable to assume that sediment being displaced to the deep ocean will carry an assortment of sediment from clay through sand sizes. It is expected that there will be differential sorting of these sizes as the sediment is moved downslope and gradually loses velocity with the sand sizes deposited first, nearest the source. Tests of Foraminifera may be considered as sand particles in their reaction to processes of sediment transportation and deposition so that any Foraminifera which are contained in the sediment will be deposited along with the sand-size material. It is expected that they will be deposited along with grains of sand smaller than the tests themselves since they have a relatively low density per unit volume. The fine silt and clay sizes of the material being displaced will be carried beyond the coarser material and deposited. This fine-grained sediment is expected to carry no tests of Foraminifera since they have been deposited with the sand.

It appears probable that some of the fine-grained sediment in the deep North Atlantic, far from sources of supply, is the fine fraction of displaced sediment. A considerable percentage of sediment in these deep basins thus may be of terrigenous origin. Deposition of the fine sediment by this mechanism should have no effect on the stratigraphic sequence of the planktonic Foraminifera in these sediments. Interpretations of chronology based upon planktonic populations in cores collected from such areas are expected to be as valid as those from any area of the ocean.

Observations on solution of the calcareous core faunas are of possible importance in studying relative rates of organic production, of deposition of sediment, and chronology. Solution observations made on the present cores are not sufficiently specific to warrant definitive applications. If most or all of the solution of calcium carbonate occurs at or near the sediment-water interface, then evidence at lower levels in a core should provide a clue to conditions at the time when any fauna was deposited. Conditions causing intensive solution may have been a relatively low rate of Foraminifera production, and perhaps other factors. It is possible that layers in the sediment containing intensive solution effects and also those containing fresh specimens are either to be correlated from area to area or have related causes. Such interpretations may be of considerable value as a check on rates of deposition estimated from other sources. They may also be of aid in certain interpretations of past environments.

Rate of deposition of deep-sea sediment is a subject on which much has been written and essentially no generalizations can be made. The writers do not intend to review the luminous literature containing speculations this subject. It seems appropriate, however, summarize our data and the interpretations ich appear to apply to this problem.

Examination of the suggested correlations tween Cores 276 to 296 on Figures 25 and suggests rather marked differences in relative position rates. The greatest contrast is tween the thickness of the uppermost higher- itude faunas (C1) in Cores 281 and 284. In re 281 this fauna (C1) is approximately cm. thick, whereas in Core 284 presumably e same fauna occurs throughout at least 400 cm. of the core, a ratio of more than : 1. Core 279 contains four higher-latitude unas and five normal-latitude in less than 0 cm., while presumably the same sequence curs in more than 1,500 cm. of Core 278. An amination of Figures 22 to 24 shows that ere are significant variations from one core to another. It is probable that relative rates of deposition vary with time at the same location.

Some of this apparent variation in sedimentation rate may, perhaps, be related to supply of fine-grained material from displaced sediments, as discussed above. Some of the relatively fast deposition undoubtedly is related to the deposition of volcanic ash. Abundant pyroclastic material was identified in some of these cores, but no systematic survey was made either of its abundance or distribution. Variations in the rate of production of the planktonic Foraminifera undoubtedly have an important effect on rate of accumulation of mineral detritus in the deep sea. Layers containing large populations of the *Globigerina* ooze assemblage which show little solution effect may indicate high production and rapid deposition.

## References

RMUDEZ, P. J.: Foraminiferos de la costa norte de Cuba. — Mem. Soc. Cubana Hist. Nat., vol. 9, pp. 129—224, 1935.

ADY, H. B.: Report on the Foraminifera dredged by H. M. S. CHALLENGER during the years 1873—1876. — Rep't. Voy. CHALLENGER, Zool. vol. 9, pp. *i-xxxi*, 1—814, 1884.

AMLETTE, M. N. and BRADLEY, W. H.: Lithology and geologic interpretations. — U. S. Geol. Surv. Prof. Paper 196-A, pt. 1, pp. 1—34, 1940.

OTZEN, F.: The Swedish Paleocene and its foraminiferal fauna. — Sver. Geol. unders., ser. c, no. 493, pp. 1—140, 1948.

LOM, G.: Los sedimentos burdigalienses de las Baleares. — Instit. Invest. Geol. Estudios Geológicos, no. 3, pp. 21—112, 1946.

LOM, G.: Estudio de los Foraminiferos de muestras de fondo recogidas entre los Cabos Juby y Bojador. — Bol. Instit. Espagñol Ocean., no. 28, pp. 28—45, 1950.

RYELL, H. M. and RIVERO, F. C.: A Miocene microfauna of Haiti. — Journ. Pal., vol. 14, no. 4, pp. 324—344, 1940.

SHMAN, J. A.: The smaller fossil Foraminifera of the Panama Canal Zone. — Bull. 103, U. S. Nat. Mus., pp. 45—87, 1918.

CUSHMAN, J. A.: Some Pliocene and Miocene Foraminifera of the Coastal Plain of the United States. — Bull. 676, U. S. Geol. Surv., pp. 1—100, 1918 a.

CUSHMAN, J. A.: The Foraminifera of the Atlantic Ocean. — Bull. 104, U. S. Nat. Mus., pt. 3, pp. 1—149, 1922.

CUSHMAN, J. A.: The Foraminifera of the Atlantic Ocean. — Bull. 104, U. S. Nat. Mus., pt. 4, pp. 1—228, 1923.

CUSHMAN, J. A.: The Foraminifera of the Atlantic Ocean. — Bull. 104, U. S. Nat. Mus., pt. 5, pp. 1—55, 1924.

CUSHMAN, J. A.: The Foraminifera of the Atlantic Ocean. — Bull. 104, U. S. Nat. Mus., pt. 8, pp. 1—179, 1931.

CUSHMAN, J. A.: A monograph of the subfamily Virgulininae of the Foraminiferal family Buliminidae. — Spec. Publ. 9, Cushman Lab. Foram. Res., pp. *vii-xv*, 1—228, 1937.

CUSHMAN, J. A. and HENBEST, L. G.: Geology and biology of North Atlantic deep-sea cores between Newfoundland and Ireland. Pt. 2, Foraminifera. — U. S. Geol. Surv. Prof. Paper 196-A, pp. 35—56, 1940.

CUSHMAN, J. A. and TODD, R.: Miocene Foraminifera from Buff Bay, Jamaica. — Spec. Publ. 15, Cushman Lab. Foram. Res., pp. 1—73, 1945.

Cushman, J. A. and Bermudez, P. J.: Some Cuban species of *Globorotalia*. — Contr. Cushman Lab. Foram. Res., vol. 25, pt. 2, pp. 26—45, 1949.

Dorsey, A.: Miocene Foraminifera from the Chesapeake group of South Maryland. — Cretaceous and Tertiary Subsurface Geology, pp. 268—327, Baltimore, Md., 1948.

Ericson, D. B., Ewing, M. and Heezen, B. C.: Turbidity currents and sediments in North Atlantic. — Bull. Amer. Assoc. Petr. Geol., vol. 36, No. 3, pp. 489—511, 1952.

Grimsdale, T. F.: Correlation, age determination, and the Tertiary pelagic Foraminifera. — Proc. 3rd World Petr. Congr., section 1, pp. 463—475, 1951.

Heron-Allen, E. and Earland, A.: Foraminifera, Clare Island Survey. — Proc. Roy. Irish Acad., vol. 31, pt. 64, pp. 1—188, 1913.

Heron-Allen, E. and Earland, A.: The Foraminifera of the west coast of Scotland. — Trans. Linn. Soc. Zool., vol. 11, pt. 13, pp. 197—299, 1916.

Hofker, J.: The toothplate-Foraminifera. — Arch. Néerl. Zool., vol. 8, livr. 4, pp. 353—372, 1951.

Höglund, H.: Foraminifera in the Gullmar Fjord and the Skagerak. — Zool. Bidrag från Uppsala, vol. 26, pp. 1—328, 1947.

Kuenen, Ph.: Properties of turbidity currents of high density. — Spec. Publ. 2, Soc. Econ. Pal. Min., pp. 14—33, 1951.

Kullenberg, B.: The piston core samples. — Svenska Hydr. Biol. Komm. Skr. 3. Ser. Hydr., vol. 1, no. 2, pp. 1—46, Göteborg, 1947.

Marks, P., Jr.: A revision of the smaller Foraminifera from the Miocene of the Vienna Basin. — Contr. Cushman Found. Foram. Res., vol. 2, pt. 2, pp. 33—73, 1951.

Mathews, R. D.: *Rectuvigerina*, a new genus of Foraminifera from a restudy of *Siphogenerina*. — Journ. Pal., vol. 19, no. 6, pp. 588—606, 1945.

Menard, H. W. and Ludwick, J. C.: Applications of hydraulics to the study of marine turbidity currents. — Spec. Publ. 2, Soc. Econ. Pal. Min., pp. 2—13, 1951.

Palmer, D. K.: Foraminifera of the Upper Oligocene Cojimar Formation of Cuba. — Mem. Soc. Cubana Hist. Nat., vol. 15, no. 3, pp. 281—306, 1941.

Parker, F. L.: Foraminifera of the continental shelf from the Gulf of Maine to Maryland. — Bull. Mus. Comp. Zool., vol. 100, no. 2, pp. 213—241, 1948.

Parker, F. L.: Foraminifera species off Portsmouth, N Hampshire. — Bull. Mus. Comp. Zool., vol. 1 no. 9, pp. 391—423, 1952.

Phleger, F. B.: Foraminifera of submarine cores fr the continental slope. Bull. Geol. Soc. Ameri vol. 50, pp. 1395—1422, 1939.

Phleger, F. B.: Foraminifera of submarine cores fr the continental slope, pt. 2. — Geol. Soc. Ameri Bull., vol. 53, pp. 1073—1098, 1942.

Phleger, F. B. and Hamilton, W. A.: Foraminifera two submarine cores from the North Atlan Basin. — Bull. Geol. Soc. America, vol. 57, p 951—966, 1946.

Phleger, F. B.: Ecology of Foraminifera, northwe Gulf of Mexico. Pt. 1, Foraminifera distributi — Geol. Soc. America, Mem. 46, pp. 1—88, 19

Phleger, F. B. and Parker, F. L.: Ecology of For minifera, northwest Golf of Mexico, Pt. 2, For minifera species. — Geol. Soc. America, Mem. 4 pp. 1—64, 1951.

Phleger, F. B.: Displaced Foraminifera faunas. — Spe Publ. 2, Soc. Econ. Pal. Min., pp. 66—75, 1951

Said, R.: The distribution of Foraminifera in the northe Red Sea. — Contr. Cushman Found. Foram. Re vol. 1, pts. 1, 2, no. 3, pp. 9—29, 1950.

Schott, W.: Die Foraminiferen in den aequatorial Teil des Atlantischen Ozeans. — Wiss. Erge Deutschen Atlantischen Exped. Forsch. u. Verme »Meteor» 1925—1927, vol. 3, pt. 3, pp. 43—13 1935.

Shepard, F. P.: Transportation of sand into deep wate — Spec. Publ. 2, Soc. Econ. Pal. Min., pp. 54— 1951.

Thalmann, H. E.: Nachtrag zum Nomenclator zu Brady Tafelband der Foraminiferen der CHALLENGE Exped. — Eclog. Geol. Helvetiae, vol. 26, no. pp. 251—255, 1933.

Thalmann, H. E.: New names and homonyms in For minifera. — Contr. Cushman Found. Foram. Re vol. 1, pts. 3, 4, pp. 41—45, 1950.

Williamson, W. C.; On the Recent Foraminifera Great Britain. — Ray Soc., London, pp. *vv-x* 1—107, 1858.

Wiseman, J. D. H. and Ovey, C. D.: Recent investig tions on the deep-sea floor. — Proc. Geol. Asso vol 61, pt. 1, pp. 28—84, 1950.

Contribution No. 14. Marine Foraminifera Laboratory.

Contribution No. 619. Scripps Institution of Oceanograph

# PLATES

## PLATE 1

Figure

1, 2, 6. *Globigerina altispira* Cushman and Jarvis. X 42. Core 234, sample 113.

3, 4, 7, 8. *Globigerina bulloides* d'Orbigny. X 42. ATLANTIS Sta. 4739.

5. *Sphaeroidina bulloides* d'Orbigny. X 70. ATLANTIS Sta. 4637.

9, 10. *Globigerina digitata* H. B. Brady. X 42. (9) Core 267, sample 88; (10) Core 252, sample 70.

11, 12. *Globigerina eggeri* Rhumbler. X 42. Short Core 226 A, sample 1.

13, 14. *Globigerina hexagona* Natland. X 51. Core 243, sample 83.

15, 16. *Globigerina inflata* d'Orbigny. X 42. Core 290, sample 3.

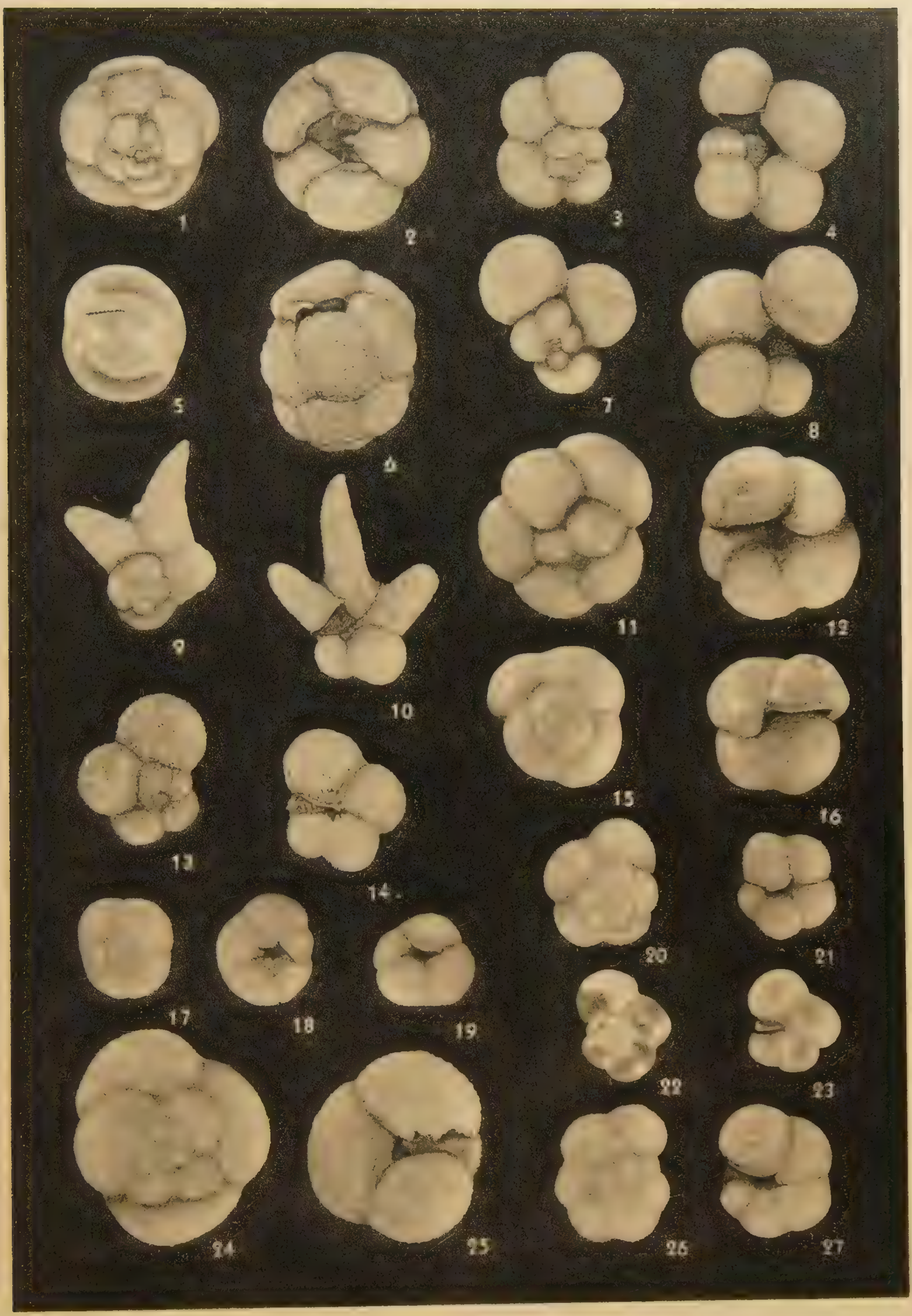
17, 18, 19. *Globigerina pachyderma* (Ehrenberg). X 51. Core 284, sample 1.

20, 21. *Globigerina quinqueloba* Natland. X 70. Core 284, sample 14.

22, 23. *Globigerina* sp. 1. X 70. Core 248, sample 89.

24, 25. *Globigerina venezuelana* Hedberg. X 42. Core 234, sample 113.

26, 27. *Globigerina* sp. 2. X 70. Core 235, sample 129.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## PLATE 2

Figure

1, 2, 3. *Globigerinoides conglobata* (H. B. Brady). X 42. (1, 2) ATLANTIS Sta. 4637; (3) Core 267, Sample 42.

4, 7. *Globigerinoides rubra* (d'Orbigny). X 42. Short Core 226 A, sample 1.

5, 6. *Globigerinoides sacculifera* (H. B. Brady). X 42. Short Core 226 A, sample 1.

8. *Orbulina universa* d'Orbigny. X 42. Short Core 267 A, sample 1.

9, 10, 11. *Globigerinella aequilateralis* (H. B. Brady). X 42. Core 242, sample 58.

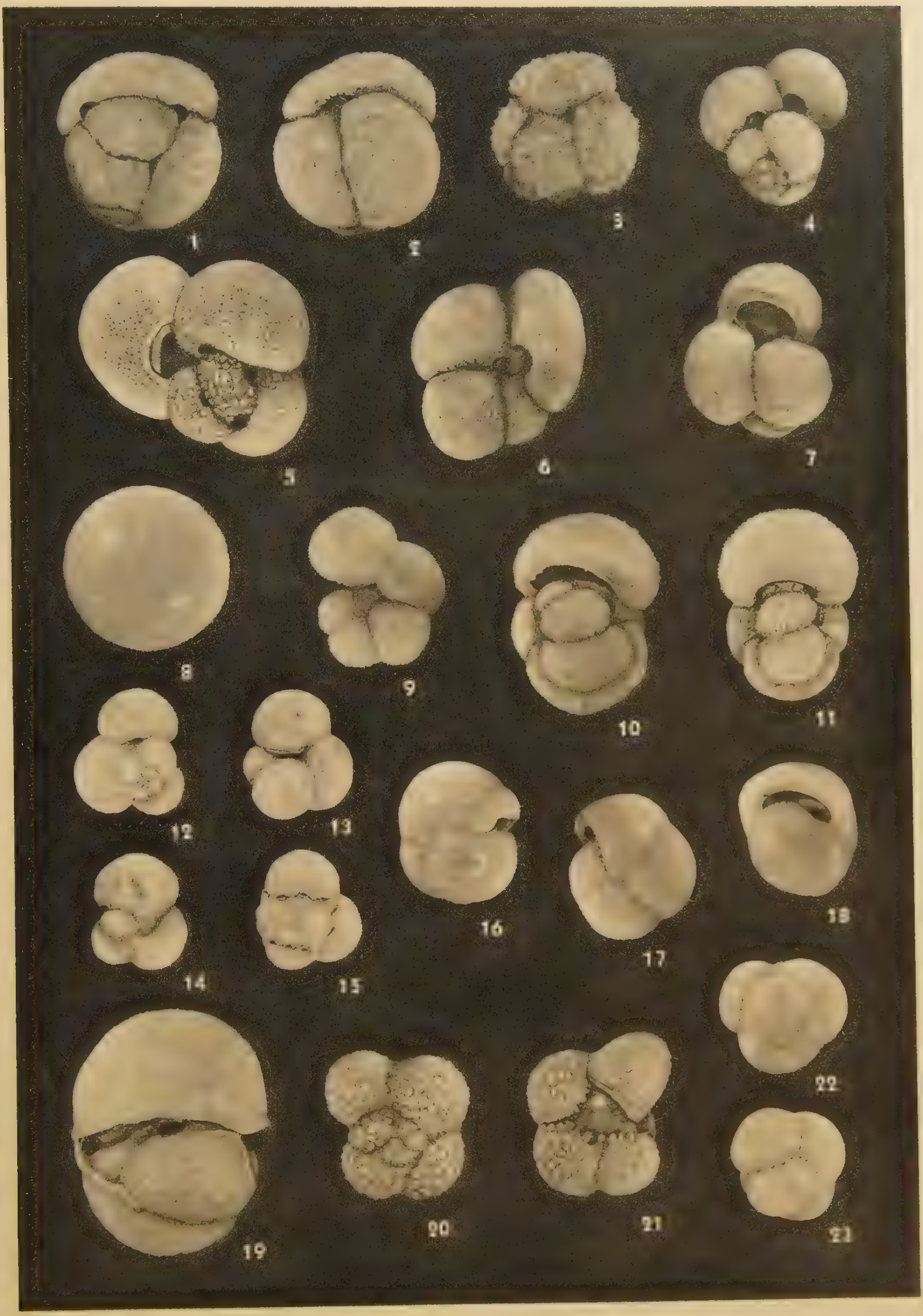
12, 13, 14, 15. *Globigerinita glutinata* (Egger). X 51. Core 228, sample 1.

16, 17, 18. *Pulleniatina obliquiloculata* (Parker and Jones). X 42. ATLANTIS Sta. 4637.

19. *Sphaeroidinella dehiscens* (Parker and Jones). X 42. Core 246, sample 48.

20, 21. *Sphaeroidinella rutschi* Cushman and Renz. X 42. Core 234, sample 128.

22, 23. *Candeina nitida* d'Orbigny. X 42. Core 267, sample 1.



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## PLATE 3

Figure

1, 2. *Globorotalia menardii* (d'Orbigny). (1) X 31; (2) X 34. Short Core 226 A, sample 1.

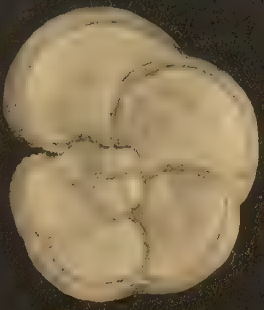
3, 6. *Globorotalia tumida* (H. B. Brady). (3) X 34; (6) X 42. Short Core 226 A, sample 1.

4, 5. *Globorotalia menardii* var. (d'Orbigny). X 34. Core 267, sample 20.

7, 8. *Globorotalia tumida* var. (H. B. Brady). X 34. Core 279, sample 143.

10, 11. *Globorotalia tumida* var. (H. B. Brady). X 34. Core 252, sample 68.

9, 12. *Globorotalia multicamerata* Cushman and Jarvis. X 42. Core 234, sample 113.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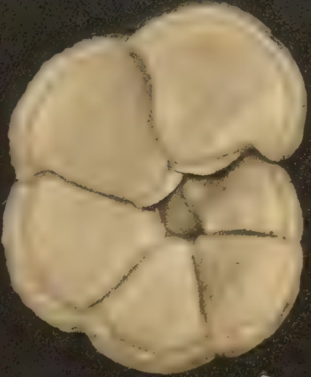
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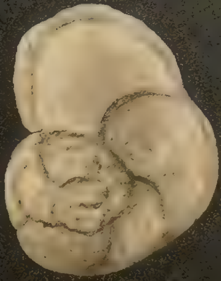
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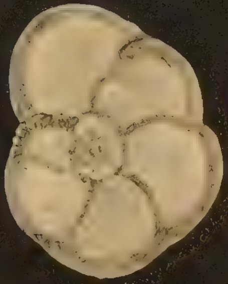
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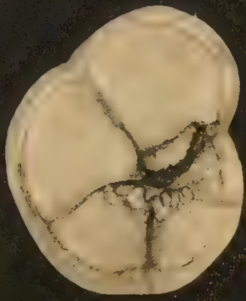
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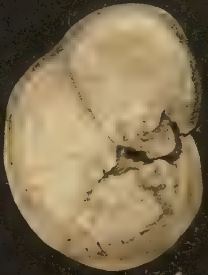
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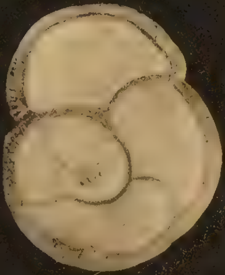
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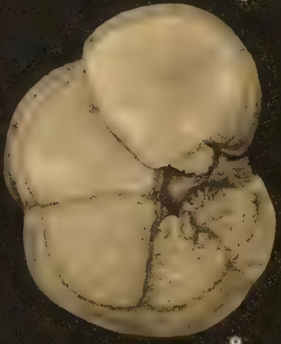
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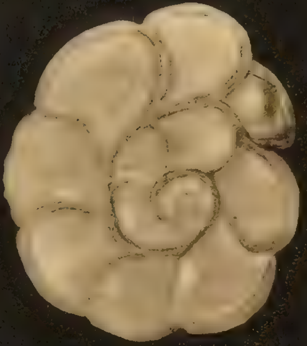
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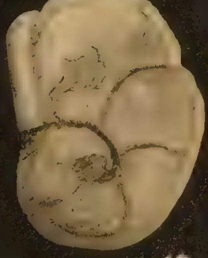
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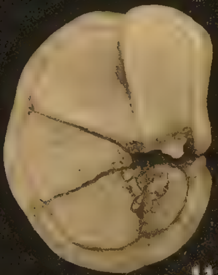
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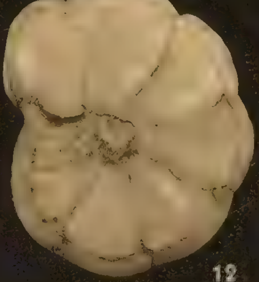
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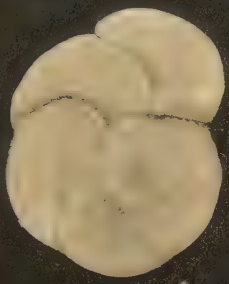
## PLATE 4

| Figure | |
|---|---|
| 1, 2, 3, 4. | *Globorotalia hirsuta* (d'Orbigny). X 42. ATLANTIS Sta. 4637. |
| 5, 6, 7. | *Globorotalia hirsuta* var. (d'Orbigny). X 42. Core 289, sample 79. |
| 8, 9, 10, 11, 12. | *Globorotalia punctulata* (d'Orbigny). (8, 12) X 34; (9, 10) X 42; (11) X 31. Core 279, sample 152. |
| 13, 14. | *Globorotalia scitula* (H. B. Brady). X 42. Core 246, sample 48. |
| 15, 16. | *Globorotalia* sp. 2. X 42. Core 252, sample 24. |
| 17, 18. | *Globorotalia truncatulinoides* (d'Orbigny). X 42. ATLANTIS Sta. 4637. |
| 19, 20, 21. | *Globorotalia* sp. 1. X 42. Core 235, sample 129. |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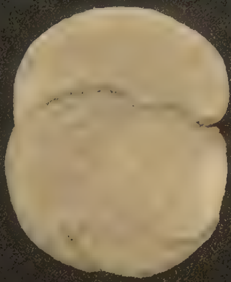
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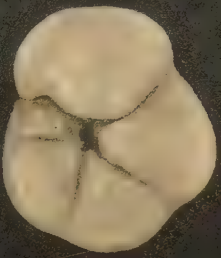
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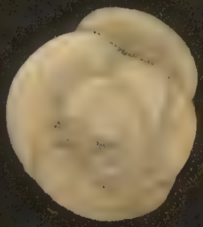
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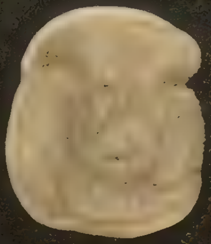
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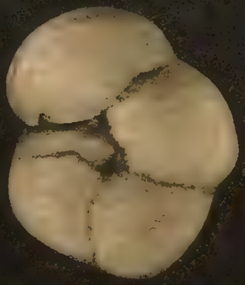
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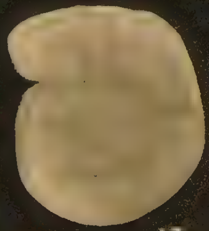
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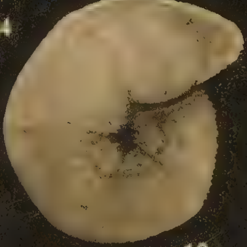
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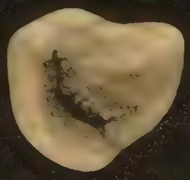
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## PLATE 5

Figure

1. *Glomospira charoides* (Jones and Parker). X 70. ATLANTIS Sta. 4735.

2. *Glomospira* cf. *gordialis* (Jones and Parker). X 51. Core 267, sample 1.

3, 4. *Textularia australis* Parr. X 51. (3) Core 279, sample 60; (4) Core 279, sample 53.

5, 6. *Siphotextularia curta* (Cushman). (5) X 42, Core 290, sample 4; (6) X 51, Core 290, sample 5.

7. *Siphotextularia rolshauseni* Phleger and Parker. X 51, Core 280, sample 99.

8, 9. *Eggerella bradyi* (Cushman). (8) X 42; (9) X 51. Core 279, sample 46.

10. *Plectina apicularis* (Cushman). X 51. ATLANTIS Sta. 4637.

11, 12. *Quinqueloculina venusta* Karrer. X 42. Core 288, sample 1.

13, 14. *Quinqueloculina* cf. *weaveri* Rau. X 42. (13) Core 246, sample 4; (14) Core 246, sample 1.

15, 16. *Spiroloculina* sp. X 51. (15) Core 280, sample 109; (16) Core 280, sample 115.

17. *Sigmoilina schlumbergeri* A. Silvestri. X 42. Core 292, sample 37.

18. *Sigmoilina tenuis* (Czjzek). X 51. Core 280, sample 117.

19, 20. *Nummoloculina irregularis* (d'Orbigny). X 51. Core 267, sample 10.

21. *Triloculina tricarinata* d'Orbigny. X 51. Core 289, sample 41.

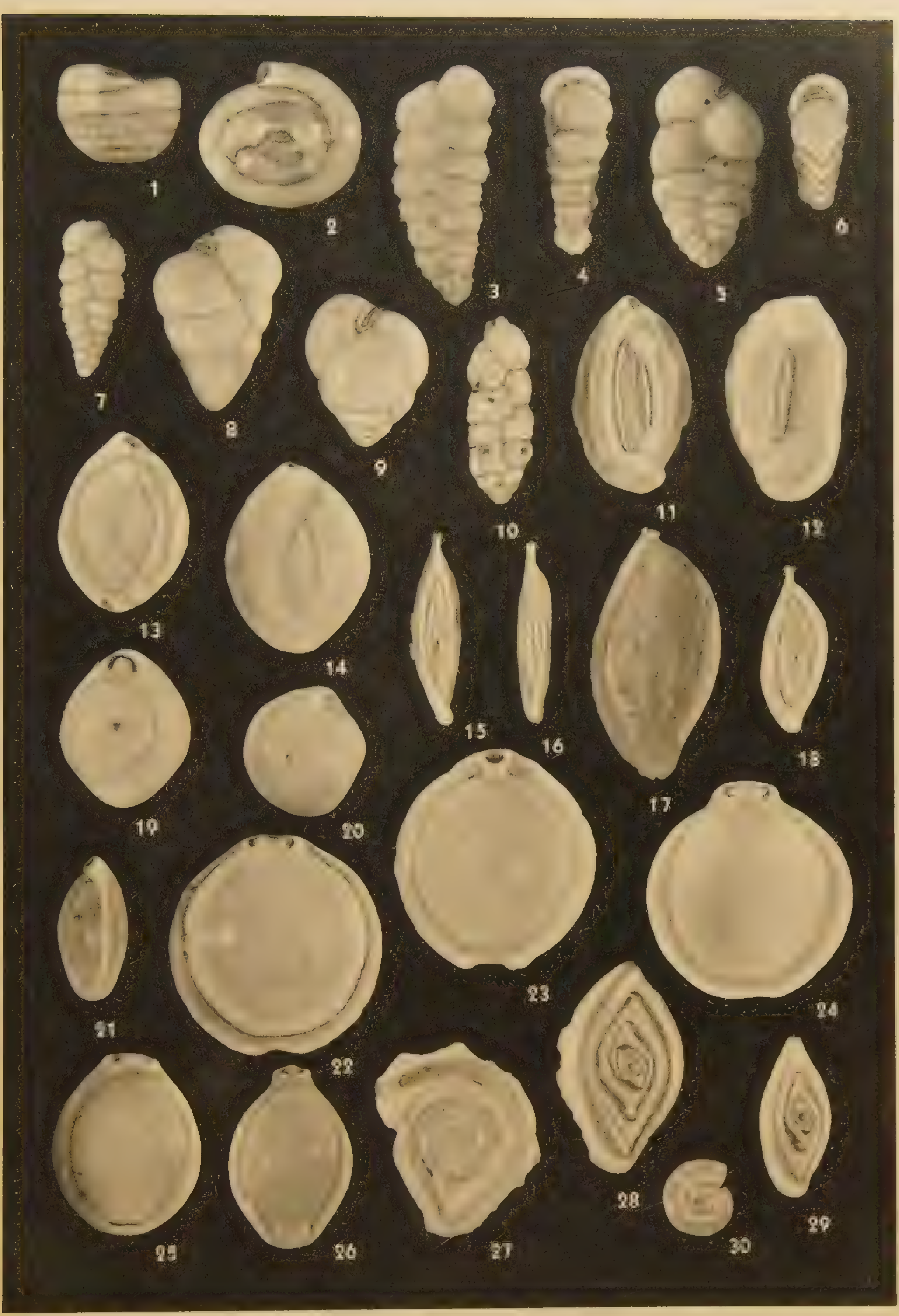
22, 23, 24. *Pyrgo murrhina* (Schwager). (22, 23) X 34. (24) X 30. (22) Core 284, sample 94; (23) Core 284, sample 56; (24) Core 279, sample 7.

25, 26. *Pyrgo oblonga* (d'Orbigny). X 42. Core 292, sample 73.

27. *Ophthalmidium inconstans* (H. B. Brady). X 51. Core 267, sample 10.

28, 29. *Spirophthalmidium acutimargo* (H. B. Brady). X 51. (28) Core 267, sample 15; (29) Core 288, sample 38.

30. *Cornuspira planorbis* Schultze. X 70. Core 248, sample 89.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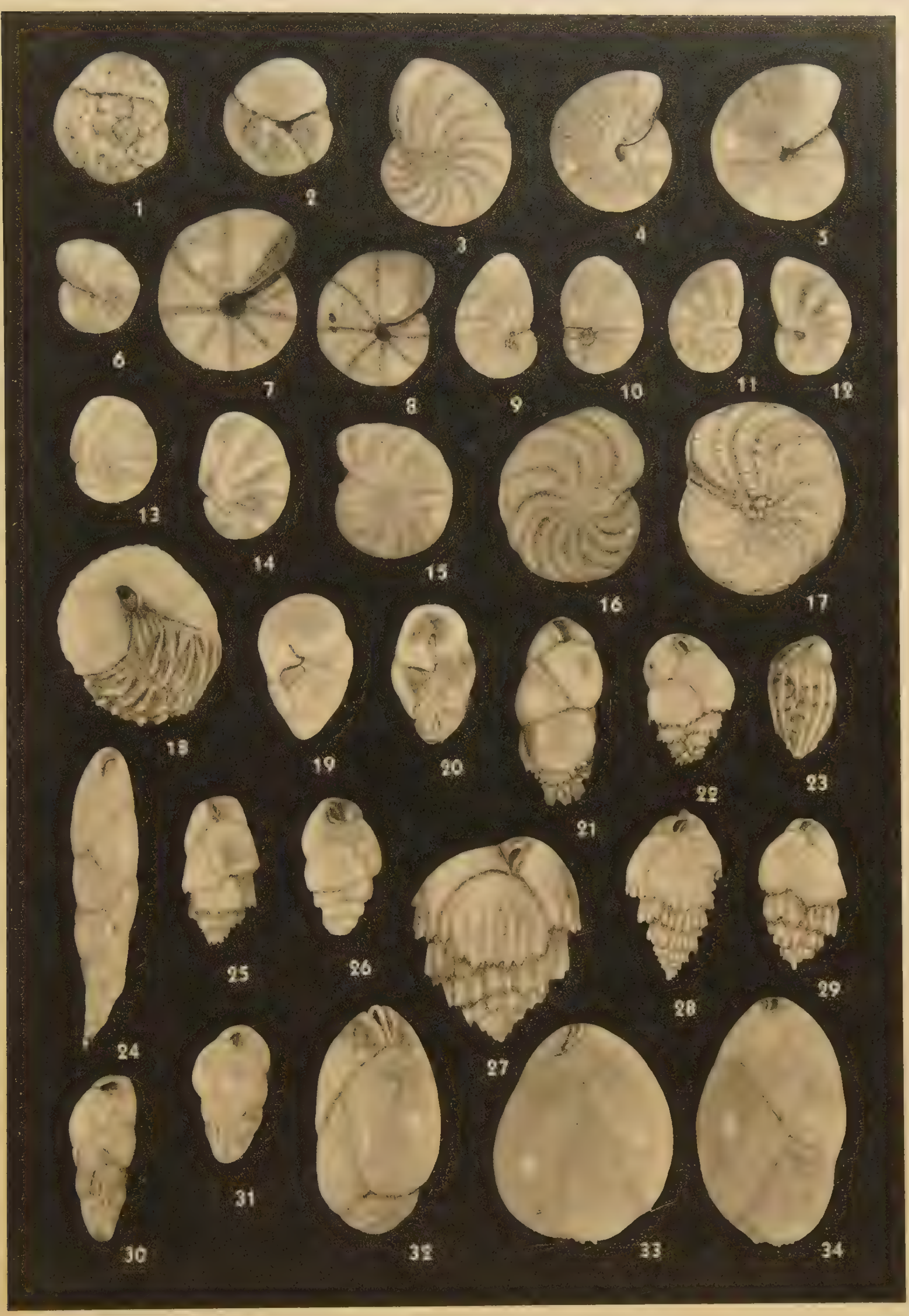
## PLATE 6

Figure

1, 2. *Trochammina* cf. *advena* Cushman. X 51. Core 267, sample 1.
3. *Nonion asterizans* (Fichtel and Moll). X 42. Core 221, sample 1.
4. *Nonion barleeanum* (Williamson). X 51. Core 246, sample 82.
5. *Nonion formosum* (Seguenza). X 51. Core 252, sample 24.
6. *Nonion germanicum* (Ehrenberg). X 51. Core 288, sample 9.
7, 8. *Nonion pompilioides* (Fichtel and Moll). X 51. (7) Core 290, sample 59; (8) Core 284, sample 86.
9, 10. *Nonionella atlantica* Cushman. X 51. Core 246, sample 24.
11, 12. *Nonionella sloanii* (d'Orbigny). X 51. Core 252, sample 70.
13, 14. *Nonionella* sp. X 70. Core 252, sample 70.
15. *Elphidium advenum* (Cushman). X 51. Core 221, sample 1.
16. *Elphidium complanatum* (d'Orbigny). X 42. Core 221, sample 1.
17. *Elphidium crispum* (Linné). X 42. Core 221, sample 1.
18. *Buliminella* sp. X 51. Core 233, sample 82.
19, 20. *Robertina bradyi* Cushman and Parker. X 51. (19) Core 288, sample 39; (20) Core 267, sample 27.
21, 22. *Bulimina aculeata* d'Orbigny. X 51. Core 290, sample 31.
23. *Bulimina alazanensis* Cushman. X 51. Core 252, sample 109.
24. *Bulimina exilis* H. B. Brady. X 51. Core 221, sample 56.
25, 26. *Bulimina marginata* d'Orbigny variant. (25) X 70. (26) X 51. Core 257, sample 86.
27. *Bulimina mexicana* Cushman. X 51. ATLANTIS Sta. 4735.
28, 29. *Bulimina* aff. *subacuminata* Cushman and R. E. Stewart. X 51. Core 221, sample 56.
30, 31. *Bulimina translucens* Parker, n.sp. X 70. (30) Holotype; (31) Paratype. ATLANTIS Sta. 4637.
32. *Globobulimina affinis* (d'Orbigny). X 51. Core 288, sample 14.
33, 34. *Globobulimina* (*Desinobulimina*) cf. *turgida* (Bailey). X 42. Core 221, sample 56.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## PLATE 7

Figure

1, 2. *Virgulina advena* Cushman. X 51. (1) Megalospheric form, Core 246, sample 69; (2) Microspheric form showing internal structure of aperture, Core 246, sample 56.

3. *Virgulina complanata* Egger. X 51. Core 284, sample 11.

4, 5. *Virgulina bradyi* Cushman. X 42. Core 284, sample 92.

6, 7. *Virgulina mexicana* Cushman. X 51. Core 221, sample 56.

8. *Virgulina tessellata* Phleger and Parker. X 70, Core 252, sample 9.

9, 10. *Virgulina* sp. X 70. Core 284, sample 11.

11. *Bolivina globulosa* Cushman. X 70. Core 267, sample 80.

12. *Bolivina* cf. *minuta* Natland. X 70. Core 290, sample 1.

13, 14. *Bolivina paula* Cushman and Cahill. X 70. (13) Core 267, sample 37; (14) Core 252, sample 19.

15, 16, 17. *Bolivina petterssoni* Parker, n. sp. (15) X 50, Holtype; (16, 17) X 51, Paratypes. Core 221, sample 56.

18, 19. *Bolivina pseudoplicata* Heron-Allen and Earland. (18) X 70. Core 267, sample 1; (19) X 51. Core 228, sample 4.

20, 21. *Bolivina pseudopunctata* Höglund. X 51. Core 284, sample 11.

22. *Bolivina pulchella* (d'Orbigny). X 70. Core 248, sample 92.

23. *Bolivina pusilla* Schwager. X 51. Core 290, sample 64.

24, 25. *Bolivina subaenariensis* Cushman. (24) X 42. (25) X 51. Core 257, sample 86.

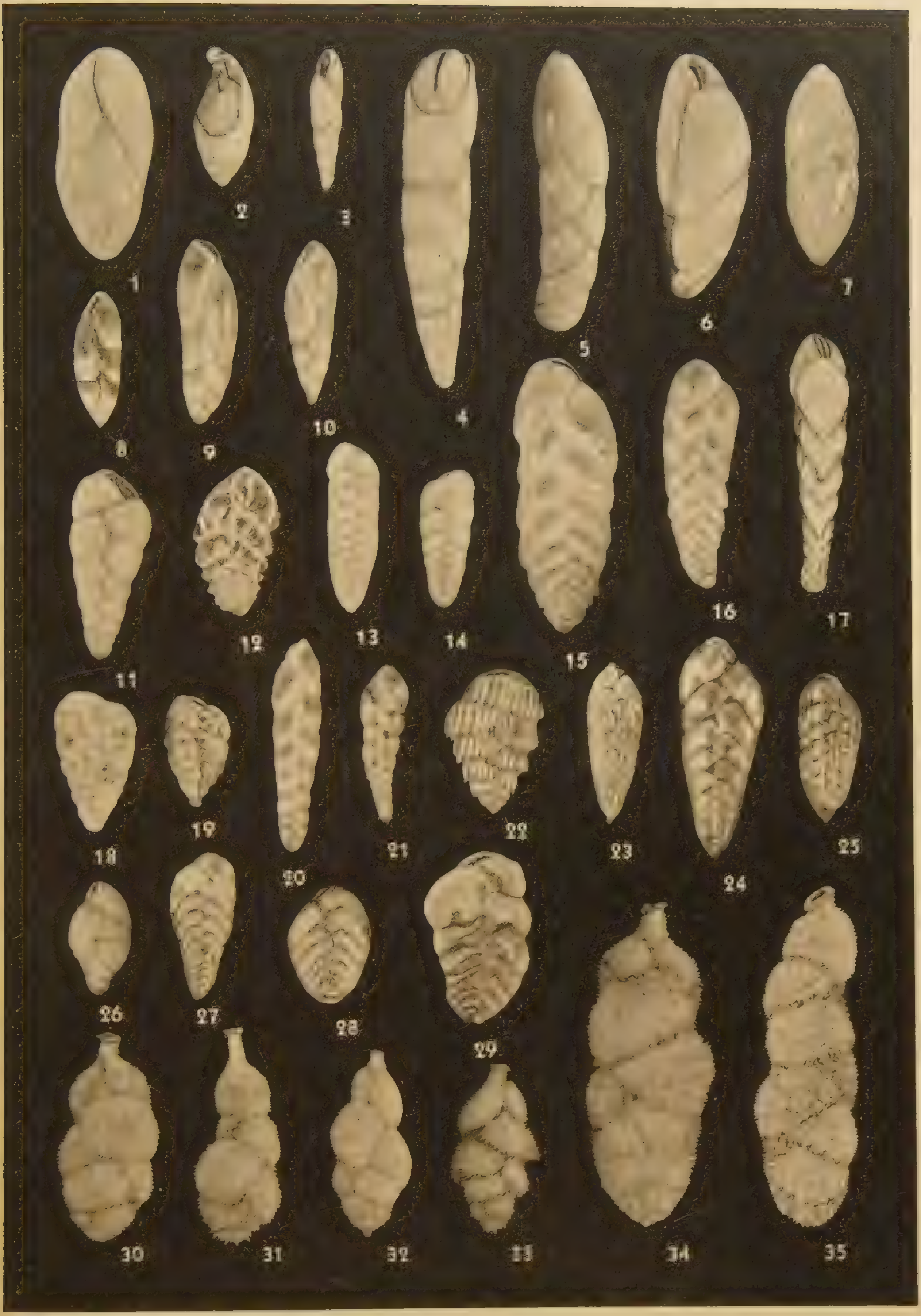
26. *Bolivina tortuosa* H. B. Brady. X 51. Core 252, sample 24.

27, 28. *Bolivina* sp. 1. X 51. Core 221, sample 10.

29. *Bolivina* sp. 2. X 51. Core 233, sample 132.

30, 31, 32. *Uvigerina auberiana* d'Orbigny. X 51. (30) Core 290, sample 64; (31) Core 290, sample 9; (32) Core 290, sample 31.

33, 34, 35. *Uvigerina auberiana* d'Orbigny variants. (33) X 51. Core 290, sample 54; (34) X 42. (35) X 30. Core 267, sample 15.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## PLATE 8

Figure

1. *Uvigerina hollicki* Thalmann. X 42. Core 284, sample 11.

2, 3. *Uvigerina hollicki* Thalmann variants. X 42. (2) Core 290, sample 64; (3) Core 284, sample 109.

4, 5. *Uvigerina senticosa* Cushman. X 51. Core 221, sample 56.

6. *Uvigerina* sp. 1. X 70. Core 257, sample 86.

7. *Uvigerina* sp. 2. X 70. Core 257, sample 87.

8. *Rectuvigerina* sp. X 51. Core 228, sample 16.

9. *Angulogerina selseyensis* (Heron-Allen and Earland). X 70. Core 267, sample 48.

10, 11, 12, 13. *Pleurostomella acuminata* Cushman. X 51. (10) Core 234, sample 138; (11) Core 234, sample 130; (12, 13) Core 242, sample 90.

14. *Patellina corrugata* Williamson. X 70. Core 248, sample 89.

15 a, b. *Discorbis bertheloti* (d'Orbigny). X 42. Core 257, sample 88.

16, 17. *Discorbis* cf. *columbiensis* Cushman. X 70. Core 267, sample 37.

18, 23, 24. *Discorbis mamilla* (Williamson). (18, 24) X 70. Core 228, sample 4; (23) X 51. Core 215, sample 48.

19, 20, 21, 22. *Discorbis williamsoni* Parr. X 51. (19) Core 290, sample 60; (20) Core 290, sample 64; (21, 22) Core 228, sample 1.

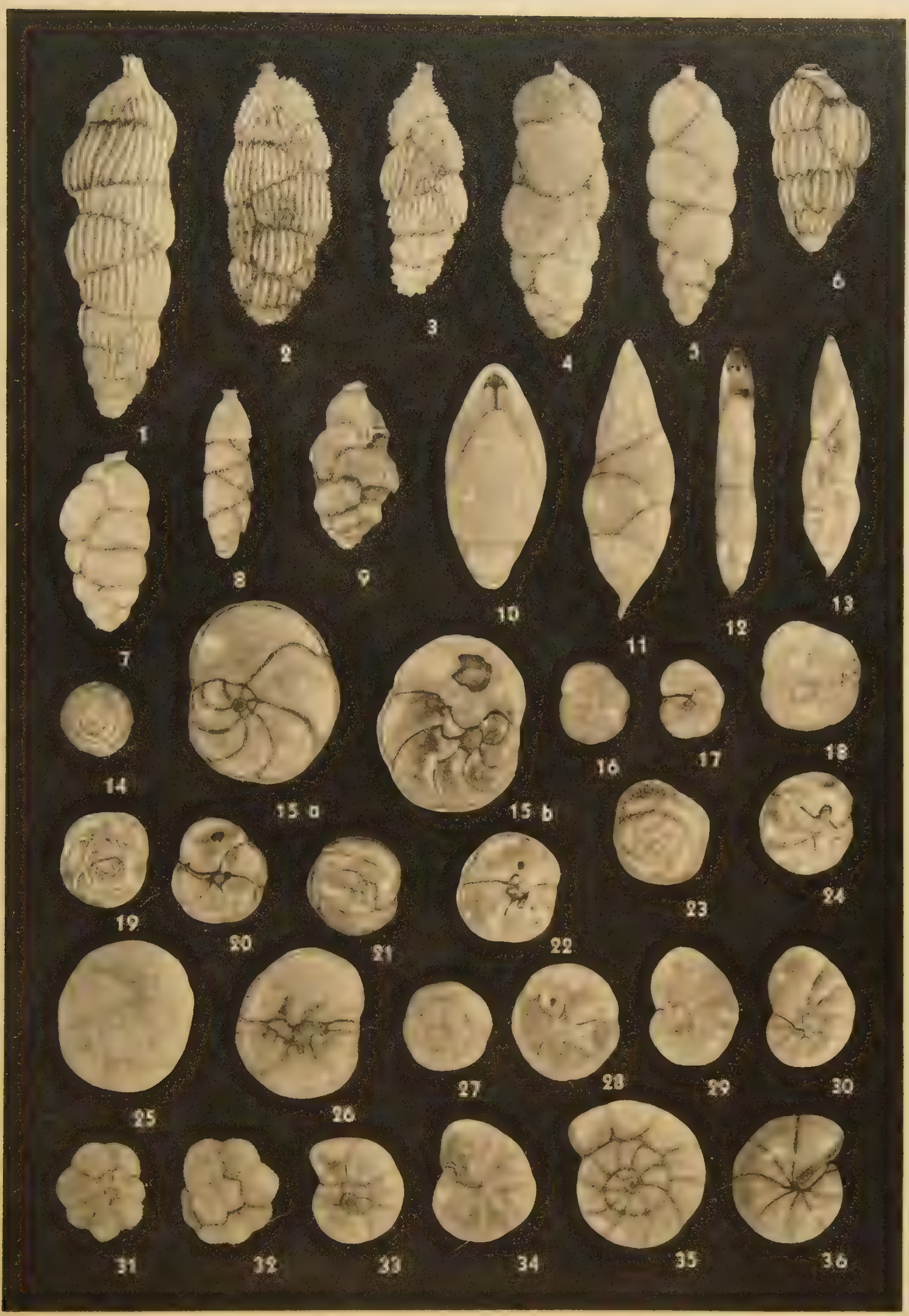
25, 26, 27, 28. *Discorbis obtusa* (d'Orbigny). (25, 26) X 42. Core 215, sample 48; (27) X 51. (28) X 70. Core 246, sample 24.

29, 30. *Valvulineria araucana* (d'Orbigny). X 51. Core 267, sample 1.

31, 32. *Valvulineria humilis* (H. B. Brady). X 70. ATLANTIS Sta. 4637.

33, 34. *Gyroidina lamarckiana* (d'Orbigny). X 51. Core 217, sample 19.

35, 36. *Gyroidina orbicularis* (d'Orbigny). X 51. Core 290, sample 4.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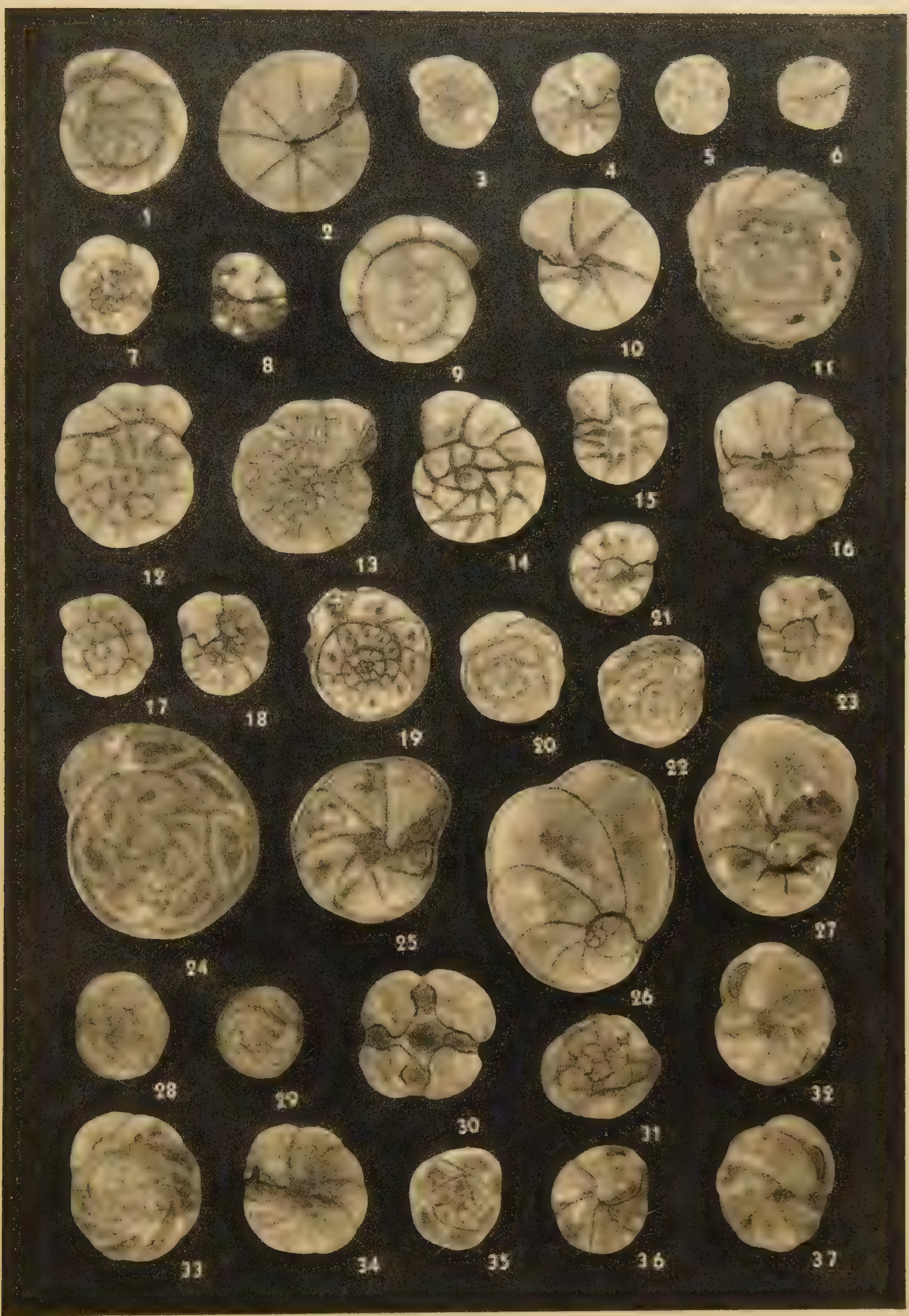
# PLATE 9

| Figure | |
|---|---|
| 1, 2. | *Gyroidina soldanii* d'Orbigny variants. X 51. Core 217, sample 19. |
| 3, 4. | *Eponides polius* Phleger and Parker. X 70. Core 246, sample 1. |
| 5, 6. | *Eponides pusillus* Parr. X 70. Core 284, sample 25. |
| 7, 8. | *Eponides tumidulus* (H. B. Brady). X 70. Core 246, sample 1. |
| 9, 10. | *Eponides umbonatus* (Reuss). X 51. Core 279, sample 23. |
| 11, 16. | *Osangularia cultur* (Parker and Jones). X 42. Core 246, sample 48. |
| 12, 13, 14, 15, 17, 18. | »*Rotalia*» beccarii (Linné) variants. X 51. (12, 13, 14, 15) Core 221, sample 1; (17, 18) Core 257, sample 86. |
| 19, 20, 21. | »*Rotalia*» *praegeri* (Heron-Allen and Earland). X 51. (19) Core 290, sample 21; (20) Core 290, sample 26; (21) Core 290, sample 16. |
| 22, 23. | »*Rotalia*» *translucens* Phleger and Parker. X 70. Core 228, sample 4. |
| 24, 25. | *Höglundina elegans* (d'Orbigny). (24) X 34. (25) X 42. Core 267, sample 10. |
| 26, 27. | *Cancris* cf. *oblonga* (Williamson). X 51. Core 221, sample 56. |
| 28, 29. | *Amphistegina lessonii* d'Orbigny. X 70. Core 267, sample 10. |
| 30, 31. | *Tretomphalus atlanticus* Cushman. X 51. Core 228, sample 1. |
| 32, 37. | *Cassidulina carinata* A. Silvestri. X 51. Core 290, sample 60. |
| 33, 34. | *Epistominella* (?) *umbonifera* (Cushman). X 51. Core 284, sample 105. |
| 35, 36. | *Epistominella exigua* (H. B. Brady). X 51. Core 292, sample 19. |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## PLATE 10

Figure

1. *Cassidulina crassa* d'Orbigny. X 70. Core 233, sample 82.

2. *Cassidulina curvata* Phleger and Parker. X 70. Core 246, sample 24.

3. *Cassidulina norcrossi australis* Phleger and Parker. X 51. Core 257, sample 86.

4. *Cassidulina subglobosa* H. B. Brady. X 51. Core 284, sample 109.

5. *Cassidulina* sp. 1. X 51. Core 215, sample 46.

6, 7. *Cassidulina reflexa* Galloway and Wissler. X 51. Core 233, (6) sample 128; (7) sample 133.

8, 9. *Cassidulina* sp. 2. (8) X 42. Core 233, sample 132; (9) X 51. Core 233, sample 133.

10, 11. *Cassidulinoides mexicana* (Cushman). X 51. Core 221, sample 56.

12 a, b, 13. *Ehrenbergina trigona* Goës. X 51. (12 a, b) Core 279, sample 23; (13) Core 242, sample 45.

14, 15 a, b, 16. *Ehrenbergina undulata* Parker, n. sp. X 51. (14, 16) Paratypes; (15 a, b) Holotype. Core 290, sample 21.

17, 23. *Rotamorphina laevigata* (Phleger and Parker). X 51. Core 228, sample 16.

18. *Chilostomella oolina* Schwager. X 51. Core 242, sample 19.

19. *Pullenia bulloides* (d'Orbigny). X 51. Core 284, sample 94.

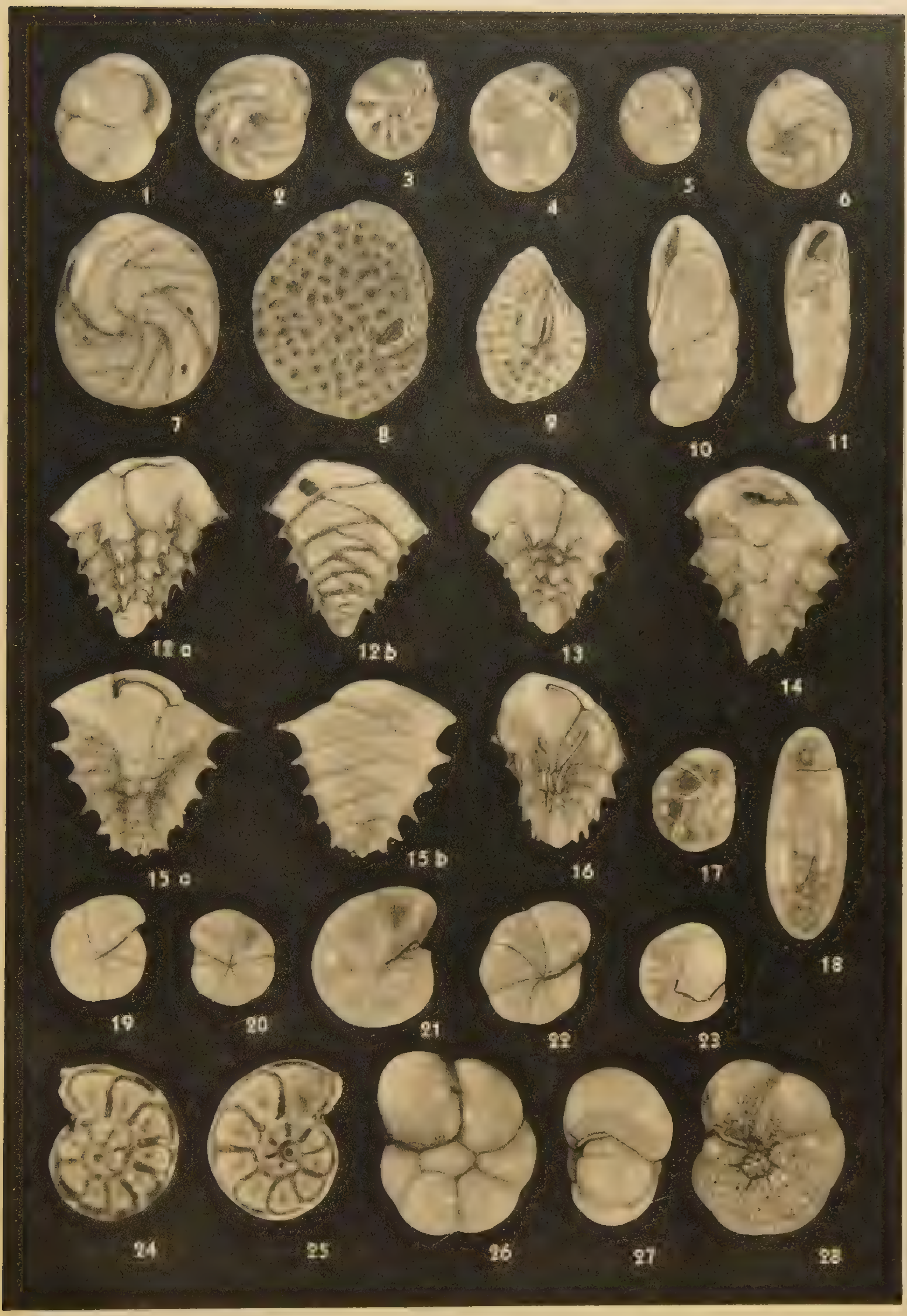
20. *Pullenia quinqueloba* (Reuss). X 51. Core 278, sample 15.

21. *Pullenia* cf. *riveroi* Bermudez. X 51. Core 267, sample 1.

22. *Pullenia* sp. X 51. Core 278, sample 13.

24, 25. *Anomalina balthica* (Schroeter). X 51. Core 221, sample 10.

26, 27, 28. *Anomalina* sp. X 51. Core 234, sample 30.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## PLATE 11

Figure

1, 2. *Planulina wuellerstorfi* (Schwager). X 42. Core 290, sample 1.

3, 4. *Planulina ariminensis* d'Orbigny. X 51. Core 290, sample 4.

5, 6. *Laticarinina pauperata* (Parker and Jones). (5) X 42. Core 267, sample 21; (6) X 30. Core 290, sample 1 B.

7, 8. *Cibicides kullenbergi* Parker, n. sp. X 42. (7) Holotype; (8) Paratype. REHOBETH Sta. 3—38.

9, 14. *Cibicides lobatulus* (Walker and Jacob). X 42. Core 221, sample 1.

10, 11. *Cibicides* cf. *refulgens* Montfort. X 51. Core 215, sample 50.

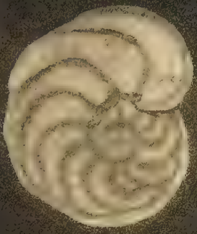
12, 13. *Cibicidina rhodiensis* (Terquem). X 51. Core 215, sample 48.

15, 16, 17. *Cibicides robertsonianus* (H. B. Brady). X 51. (15, 16) Core 217, sample 15; (17) Core 288, sample 38.

18, 22. *Cibicides* sp. (18) X 51. (22) X 42. Core 288, sample 39.

19. *Rupertia stabilis* Wallich. X 30. Core 290, sample 1 A.

20, 21. *Planorbulina mediterranensis* d'Orbigny. X 51. Core 221, sample 1.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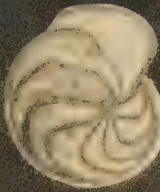
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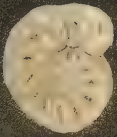
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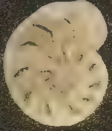
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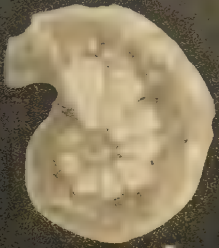
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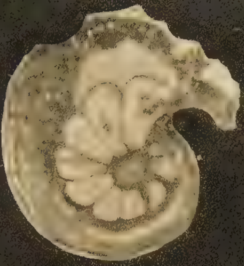
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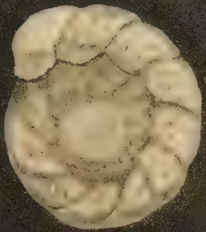
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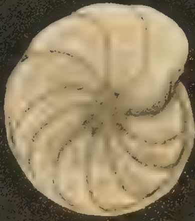
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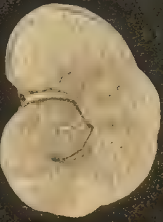
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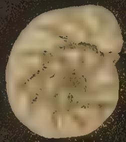
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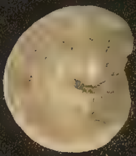
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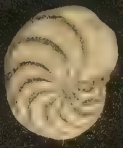
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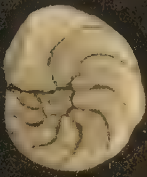
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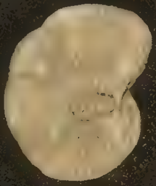
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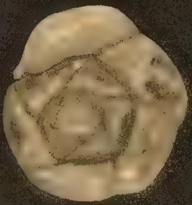
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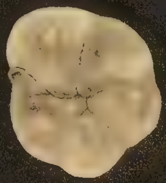
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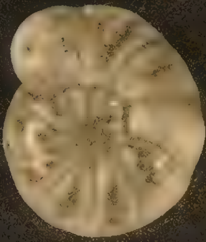
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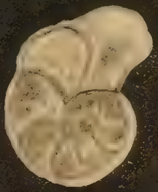
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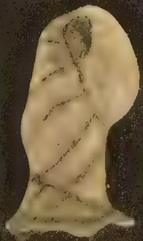
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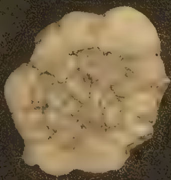
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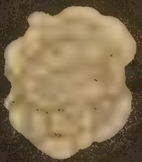
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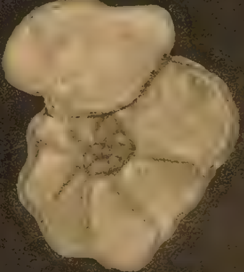
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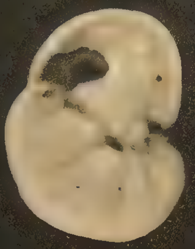
# PLATE 12.

Specimens of the *Globorotalia menardii-tumida* group showing solution of calcium carbonate. X 40. (approx.) Photographs are not retouched.



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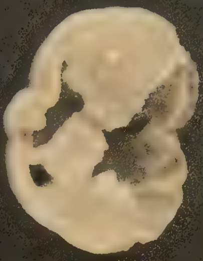

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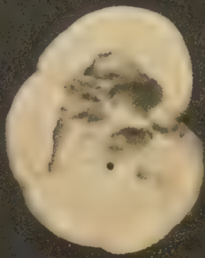

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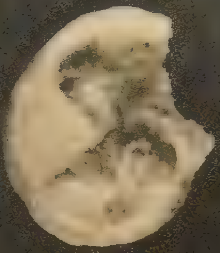

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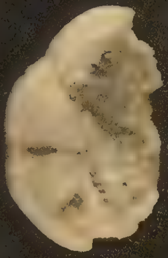

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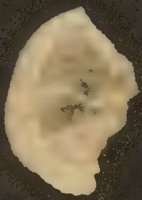

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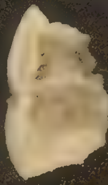

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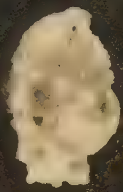

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# CIRCULATION IN THE UPPER MIXED LAYER OF THE EQUATORIAL NORTH PACIFIC[1]

By

KOZO YOSHIDA, HAN-LEE MAO AND PAUL L. HORRER

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## ABSTRACT

The circulation in the upper mixed layer in the equatorial region of the North Pacific is treated by solving the steady-state equations containing terms of Corioli's force, pressure gradient, and horizontal as well as vertical mixing. Assumptions made include: (1) The coefficient of vertical eddy viscosity is constant in the top homogeneous layer and vanishes at the bottom of the layer; (2) the horizontal velocity field may be approximated by a sinusoidal function, and thus horizontal mixing terms may be chosen in simple form; and (3) the mean wind-stress distribution and mean density distribution suggested by Reid are generally applicable. Mathematical development of the vertical motion is carried out in detail and numerical results are obtained. Agreement of the results obtained herein with available observed data and theoretical considerations by other investigators is discussed.

## INTRODUCTION

During recent years, considerable progress has been made in the theoretical development of mass transport associated with the general oceanic circulation by Stockmann (1946b), Sverdrup (1947), Reid (1948a), Stommel (1948), Munk (1950), Hidaka (1951), and others. In these papers, however, the character of the vertical distribution of density is not specified and hence no vertical profile of current was obtained. Stockmann (1946a) and Hidaka and Takano (1952) dealt with the current profile but made the assumption of homogeneous water which is not very well justified in the actual case. Until the recent work of Weenink and Groen (1952), which appeared when our present investigation was nearly completed, the treatment by Defant (1936) for the Atlantic was still considered the classic of circulation in the upper mixed layer of the equatorial ocean. Defant's assumptions of no motion in the underlying water mass and of no net meridional transport of water ($M_y = 0$) in the upper mixed layer, and his approach of preassuming the value of surface current velocities, are questionable, especially in the light of recent knowledge. Some of Weenink

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 620

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and Groen's assumptions differ from those made in the following discussion, but their computational results were not made available. Thus, the ensuing treatment reconsiders the problem of circulation in the upper mixed layer of the equatorial Pacific, with emphasis on detailed discussion of the vertical motion, an aspect not included in previous works.

## BASIC THEORY

Let the $x$-axis be positive eastward along the equator, the $y$-axis northward, and the $z$-axis vertically downward from the undisturbed level surface. The terms of horizontal mixing may be chosen as $-ku$ and $-kv$ as a close first approximation when $u$ and $v$, the eastward and northward components of the current velocity respectively, vary sinusoidally with latitude, which, as we shall see later, is the case in the area considered. The coefficient of the vertical eddy viscosity is assumed constant in the upper mixed layer. If the nonlinear terms and the term including the vertical motion (i. e., $2\omega \cos \varphi w$) are considered negligible, the equations of steady horizontal motion are

$$\begin{aligned} -\lambda v &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(A\frac{\partial u}{\partial z}\right) - ku \\ \lambda u &= -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\frac{\partial}{\partial z}\left(A\frac{\partial v}{\partial z}\right) - kv\,, \end{aligned} \tag{1}$$

where $p$ is pressure, $\rho$ is density, $A$ is the coefficient of vertical mixing, $\lambda$ is Corioli's parameter given by $\lambda = 2\omega \sin \varphi$, $\omega$ is the angular velocity of the earth's rotation, and $\varphi$ is latitude.

The parameter $k$ (which may be called the "mixing number") is defined by

$$k = \frac{4\pi^2}{L^2}B\,, \tag{2}$$

where $B$ is the coefficient of horizontal mixing and $L$ is the wave length of the sinusoidal horizontal velocity profile. Generally the parameter $k$ may be assumed as a function of the $y$-coordinate in the form of $-k(y)u$ and $-k(y)v$. (Recall that $\lambda$ also varies with the $y$-coordinate.)

Let $u$ and $v$ be separated into two parts as follows:

$$\begin{aligned} u &= u_1(x, y) + u_2(x, y, z) \\ v &= v_1(x, y) + v_2(x, y, z)\,, \end{aligned} \tag{3}$$

where $u_1$, $v_1$ and $u_2$, $v_2$ compose the "gradient current" and "drift current" respectively.

The pressure at any depth can be determined from the hydrostatic equation by using Reid's (1948b) model for the distribution of density

$$\begin{aligned} \rho &= \rho_o & &\text{for } z \leqslant h\,(x, y) \\ \rho\,(x, y, z) &= \rho_d - \Delta\rho e^{1-z/h} & &\text{for } z \geqq h\,(x, y)\,, \end{aligned} \tag{4}$$

where $\Delta\rho = \rho_d - \rho_0$ and $h$ is the lower boundary of the homogeneous layer.

Thus, the equations for $u_1$ and $v_1$ are

$$\left.\begin{aligned} -\lambda v_1 &= -\frac{1}{\rho_0}\frac{\partial p}{\partial x} - ku_1 \\ \lambda u_1 &= -\frac{1}{\rho_0}\frac{\partial p}{\partial y} - kv_1 \end{aligned}\right] \text{for } z \leqslant h\,. \tag{5}$$

For simplicity, the subscript $_0$ in the density $\rho_0$ shall be dropped henceforth, since only the upper mixed water layer is of concern in this study. No attempt shall be made to discuss the motion in the underlying layer.

Then the solution of equation (5) can be given by

$$\begin{aligned} u_1 &= \frac{1}{\lambda^2 + k^2}\left(\frac{k}{\rho}\frac{\partial p}{\partial x} + \frac{\lambda}{\rho}\frac{\partial p}{\partial y}\right) \\ v_1 &= \frac{1}{\lambda^2 + k^2}\left(\frac{\lambda}{\rho}\frac{\partial p}{\partial x} - \frac{k}{\rho}\frac{\partial p}{\partial y}\right). \end{aligned} \tag{6}$$

For $u_2$ and $v_2$ we have

$$\begin{aligned} -\lambda v_2 &= \frac{A}{\rho}\frac{\partial^2 u_2}{\partial z^2} - ku_2 \\ \lambda u_2 &= \frac{A}{\rho}\frac{\partial^2 v_2}{\partial z^2} - kv_2\,. \end{aligned} \tag{7}$$

As boundary conditions we assume

$$\begin{aligned} \left.\frac{\partial u_2}{\partial z}\right|_{z=0} &= -\frac{\tau_x(y)}{A} \\ \left.\frac{\partial v_2}{\partial z}\right|_{z=0} &= -\frac{\tau_y(y)}{A} \\ \left.\frac{\partial u_2}{\partial z}\right|_{z=h} &= \left.\frac{\partial v_2}{\partial z}\right|_{z=h} = 0\,. \end{aligned} \tag{8}$$

The last equation indicates that $A$ is discontinuous at $z = h$, being zero at this depth and constant above it. This equation is postulated with the understanding that the stress be continuous at the boundary.

The assumption that $A$ is discontinuous at $z = h$, as a first approximation, is in fair agreement with the result of Munk and Anderson (1948) and is in accord with our present knowledge.

Under these assumptions,[2] we have

$$u_2 = \frac{U}{A\ (m^2 + n^2)(\cosh 2\theta - \cos 2\theta_1)}$$
$$v_2 = \frac{V}{A\ (m^2 + n^2)(\cosh 2\theta - \cos 2\theta_1)}\,, \qquad (9)$$

where

$U = (m\tau_x + n\tau_y)\,F_1 + (m\tau_y - n\tau_x)\,F_2$,

$V = (m\tau_y - n\tau_x)\,F_1 - (m\tau_x + n\tau_y)\,F_2$,

$F_1 = \sinh mz \cos(2\theta_1 - nz) + \sinh(2\theta - mz)\cos nz$,

$F_2 = \cosh mz \sin(2\theta_1 - nz) + \cosh(2\theta - mz)\sin nz$,

$m = \sqrt{\rho\,(k_1 + k)/2A}$,

$n = \sqrt{\rho\,(k_1 - k)/2A}$,

$k_1 = \sqrt{k^2 + \lambda^2}$,

$\theta = mh, \quad \theta_1 = nh$, and

$\tau_x$ and $\tau_y$ are components of wind stress.

For $\varphi = 0$, we have

$$u_1 = -\frac{1}{k\rho}\frac{\partial p}{\partial x} \qquad v_1 = -\frac{1}{k\rho}\frac{\partial p}{\partial y}$$
$$u_2 = \frac{\tau_x\,\{\sinh mz + \sinh(2\theta - mz)\}}{Am\,(\cosh 2\theta - 1)} \qquad (10)$$
$$v_2 = \frac{\tau_y\,\{\sinh mz + \sinh(2\theta - mz)\}}{Am\,(\cosh 2\theta - 1)}\,.$$

---

[2] It is easily seen from our basic differential equation (1) that no lateral boundary condition is explicitly required to obtain our solutions. However, since $\partial p/\partial x$, $\partial p/\partial y$ and $h$ are derived from mass-transport theory, which is based on the integrated forms of equation (1), in which a lateral boundary condition ($M_x = 0$ at eastern boundary) is used, our solutions satisfy this same lateral boundary condition.

As to the equation of continuity, the three-dimensional form will be taken into consideration in our later section on vertical motion. In this section on the discussions of horizontal motion, which is based on the approximate equation (1), only the integrated equation of continuity is used to derive the values of $\partial p/\partial x$, $\partial p/\partial y$ and $h$.

It can be shown that, except for the region of low latitudes, Reid's values of $\partial p/\partial x$, $\partial p/\partial y$ and $h$ (see Discussion) are very close to ours. We shall see later that, for our numerical computations, Reid's values of these quantities have been actually used for $\phi > 7°$ N.

## COMPUTATIONS

Using equations (6), (9) and (10) in the previous section, numerical computations of $u$ and $v$ can be performed. $\partial p/\partial x$ and $\partial p/\partial y$ in equation (6) may be derived with sufficient accuracy from the model of density distribution given by Reid (1948b). Hence, we have

$$\begin{aligned} \frac{\partial p}{\partial x} &= g\rho \frac{\partial \zeta}{\partial x} = 2\, g \Delta\rho \frac{\partial h}{\partial x} = \frac{2}{5h}\frac{\partial P}{\partial x} \\ \frac{\partial p}{\partial y} &= g\rho \frac{\partial \zeta}{\partial y} = 2\, g \Delta\rho \frac{\partial h}{\partial y} = \frac{2}{5h}\frac{\partial P}{\partial y}, \end{aligned} \tag{11}$$

where $P$ is the vertically integrated pressure from the surface to the level of no motion, $g$ is the acceleration of gravity, and $\zeta = \zeta\,(x, y)$ is the elevation of the surface.

Thus, for numerical computation, equation (6) may be transformed into

$$\begin{aligned} u_1 &= -\frac{2}{5\,(\lambda^2 + k^2)\,\rho h}\,(kf_1 + \lambda f_2) \\ v_1 &= \frac{2}{5\,(\lambda^2 + k^2)\,\rho h}\,(\lambda f_1 - kf_2)\,, \end{aligned} \tag{12}$$

where $f_1 = \Delta P/\Delta x$ and $f_2 = \partial P/\partial y$, after Reid (1948a).

In the computations, use has also been made of Reid's model value of $h$ except for $\varphi \lesssim 7°$ N, where it differs considerably (cf. Reid, 1948b: figs. 2, 3) from the actual distribution shown by the CARNEGIE data (Sverdrup, et al., 1944); therefore the CARNEGIE data have been used for this region. As to the parameter $k$, values of $5 \times 10^{-6}$, $2.5 \times 10^{-6}$ and $1 \times 10^{-6}$ are used respectively for $\varphi = 0°$, $1°$, and $2°$ or greater. Further discussion about these are given in the last section. The coefficient of vertical eddy viscosity, $A$, which appears in equation (9), is assumed to be $10^2$ cgs units, which seems reasonable according to Sverdrup, et al. (1946: 484) and Hidaka, et al. (1951). The numerical results $u$ and $v$ for each latitude,[3] obtained by summing the "gradient current" and "drift current," are tabulated in Tables IA and IB. Values of $u$ and $v$ at surface and at $z = h$ are illustrated in Figs. 1a and 1b. Characteristic profiles of velocity components in the South Equatorial Current, Equatorial Counter Current and North Equatorial Current are shown in Figs. 2a to 2c.

[3] Since the pressure field and velocity field are determined from the wind stress field, to which only mean values for all longitudes considered are given, any variation in longitudinal direction is not of concern in our study.

TABLE I-A—Distribution of East-West Component ($u$) of Current Velocity in the Equatorial North Pacific (in cm/sec)

| Depth (m) | LATITUDE (°) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 0 | −20.8 | −10.5 | −1.8 | 2.9 | 7.7 | 12.1 | 17.5 | 23.4 | 33.6 | 38.1 | 14.4 | −0.8 | −15.0 | −23.5 | −27.2 | −26.5 | −36.1 | −26.5 | −24.3 | −20.3 | −20.4 |
| 5 | −20.0 | −8.9 | −0.5 | 3.9 | 8.3 | 12.6 | 17.9 | 23.7 | 34.1 | 38.7 | 15.3 | 0.2 | −13.8 | −22.4 | −25.9 | −24.9 | −33.8 | −24.3 | −22.1 | −17.8 | −18.1 |
| 10 | −19.2 | −7.5 | 0.7 | 4.6 | 8.8 | 12.9 | 18.0 | 23.7 | 34.3 | 39.3 | 15.7 | 0.8 | −13.4 | −21.0 | −24.4 | −23.3 | −31.7 | −22.2 | −20.0 | −16.1 | −14.8 |
| 15 | −18.5 | −6.3 | 1.6 | 5.2 | 8.9 | 13.0 | 18.0 | 23.6 | 34.4 | 39.6 | 16.1 | 1.1 | — | −21.1 | −23.7 | −22.1 | −29.7 | −20.2 | −18.1 | −14.1 | −12.5 |
| 20 | −17.7 | −5.2 | 2.4 | 5.5 | 9.0 | 12.9 | 17.8 | 23.4 | 34.5 | 39.9 | 16.6 | — | — | — | −23.3 | −21.3 | −28.1 | −18.6 | −16.5 | −12.9 | −10.3 |
| 25 | −17.1 | −4.2 | 3.0 | 5.7 | 8.9 | 12.7 | 17.5 | 23.0 | 34.5 | 40.1 | 17.0 | — | — | — | — | −21.0 | −26.9 | −17.3 | −15.1 | −11.8 | −8.9 |
| 30 | −16.5 | −3.4 | 3.6 | 5.8 | 8.8 | 12.4 | 17.2 | 22.8 | 34.5 | 40.3 | — | — | — | — | — | — | −26.2 | −16.2 | −14.2 | −11.0 | −7.7 |
| 35 | −15.9 | −2.7 | 4.0 | 5.8 | 8.5 | 12.0 | 16.8 | 22.4 | 34.4 | 40.3 | — | — | — | — | — | — | −26.0 | −15.5 | −13.4 | −10.4 | −7.0 |
| 40 | −15.4 | −2.0 | 4.4 | 5.8 | 8.1 | 11.6 | 16.4 | 22.1 | 34.3 | — | — | — | — | — | — | — | — | −15.1 | −12.9 | −10.0 | −6.5 |
| 45 | −14.9 | −1.4 | 4.6 | 5.5 | 7.7 | 11.2 | 16.0 | 21.8 | 34.2 | — | — | — | — | — | — | — | — | −14.9 | −12.6 | −9.7 | −6.3 |
| 50 | −14.5 | −1.0 | 4.9 | 5.5 | 7.3 | 10.8 | 15.6 | 21.5 | 34.2 | — | — | — | — | — | — | — | — | — | −12.4 | −9.7 | −6.2 |
| 55 | −14.1 | −0.5 | 5.0 | 5.2 | 6.9 | 10.3 | 15.3 | 21.3 | 34.1 | — | — | — | — | — | — | — | — | — | −12.4 | −9.6 | −6.3 |
| 60 | −13.7 | −0.2 | 5.1 | 5.0 | 6.5 | 9.9 | 15.0 | 20.9 | 34.1 | — | — | — | — | — | — | — | — | — | — | −9.6 | −6.4 |
| 65 | −13.4 | 0.0 | 5.2 | 4.8 | 6.2 | 9.6 | 14.7 | 20.7 | — | — | — | — | — | — | — | — | — | — | — | −9.6 | −6.5 |
| 70 | −13.1 | 0.3 | 5.3 | 4.6 | 5.8 | 9.2 | 14.4 | 20.5 | — | — | — | — | — | — | — | — | — | — | — | — | −6.5 |
| 75 | −12.9 | 0.4 | 5.3 | 4.4 | 5.5 | 8.9 | 14.2 | 20.4 | — | — | — | — | — | — | — | — | — | — | — | — | −6.6 |
| 80 | −12.6 | 0.5 | 5.3 | 4.2 | 5.2 | 8.6 | 14.0 | 20.3 | — | — | — | — | — | — | — | — | — | — | — | — | −6.6 |
| 85 | — | 0.5 | 5.3 | 4.1 | 5.0 | 8.3 | 13.8 | 20.2 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 90 | — | — | 5.4 | 4.0 | 4.8 | 8.1 | 13.6 | 20.1 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 95 | — | — | 5.4 | 3.9 | 4.7 | 7.9 | 13.5 | 20.0 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 100 | — | — | — | 3.9 | 4.6 | 7.8 | 13.4 | 20.0 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 105 | — | — | — | — | 4.6 | 7.7 | 13.4 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 110 | — | — | — | — | — | 7.6 | 13.4 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 115 | — | — | — | — | — | 7.5 | 13.3 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 120 | — | — | — | — | — | 7.5 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 125 | — | — | — | — | — | 7.5 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |

TABLE I-B—DISTRIBUTION OF NORTH-SOUTH COMPONENT ($v$) OF CURRENT VELOCITY IN THE EQUATORIAL NORTH PACIFIC (IN CM/SEC)

| Depth (m) | LATITUDE (°) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 0 | 5.8 | 17.3 | 13.4 | 13.1 | 11.9 | 10.4 | 8.4 | 6.9 | 5.5 | 4.0 | 3.7 | 6.8 | 12.4 | 7.6 | 2.5 | −0.7 | −2.7 | −3.1 | −3.1 | −2.6 | −2.9 |
| 5 | 5.6 | 16.3 | 12.0 | 11.3 | 10.0 | 8.6 | 6.9 | 5.6 | 5.0 | 4.2 | 4.6 | 8.4 | 13.8 | 8.3 | 4.7 | 1.7 | 0.0 | −0.7 | −0.7 | −0.3 | 0.3 |
| 10 | 5.4 | 15.4 | 10.0 | 9.4 | 8.2 | 7.0 | 5.4 | 4.5 | 4.5 | 4.2 | 5.4 | 9.4 | 14.5 | 9.5 | 6.2 | 3.3 | 1.6 | 0.8 | 0.7 | 0.9 | 2.0 |
| 15 | 5.2 | 14.5 | 9.3 | 7.8 | 6.6 | 5.5 | 4.3 | 3.6 | 3.9 | 4.2 | 5.9 | 9.9 | — | 9.8 | 6.7 | 4.2 | 2.8 | 1.7 | 1.4 | 1.4 | 2.2 |
| 20 | 5.0 | 13.7 | 7.9 | 6.2 | 5.1 | 4.3 | 3.3 | 2.8 | 3.5 | 4.2 | 6.1 | — | — | — | 7.2 | 4.9 | 3.3 | 2.0 | 1.7 | 1.6 | 2.9 |
| 25 | 4.8 | 12.9 | 6.7 | 4.9 | 3.8 | 3.1 | 2.4 | 2.1 | 3.1 | 4.2 | 6.1 | — | — | — | — | 5.1 | 3.7 | 2.1 | 1.4 | 1.4 | 2.8 |
| 30 | 4.7 | 12.3 | 5.4 | 3.6 | 2.7 | 2.1 | 1.7 | 1.6 | 2.9 | 4.2 | — | — | — | — | — | — | 3.9 | 1.9 | 1.2 | 1.0 | 2.2 |
| 35 | 4.5 | 11.8 | 4.3 | 2.4 | 1.6 | 1.3 | 1.1 | 1.2 | 2.5 | 4.1 | — | — | — | — | — | — | 3.9 | 1.8 | 0.7 | 0.6 | 1.3 |
| 40 | 4.4 | 11.1 | 3.5 | 1.4 | 0.8 | 0.7 | 0.6 | 0.9 | 2.3 | — | — | — | — | — | — | — | — | 1.7 | 0.3 | 0.1 | 1.0 |
| 45 | 4.2 | 10.5 | 2.6 | 0.4 | 0.1 | 0.1 | 0.3 | 0.7 | 2.2 | — | — | — | — | — | — | — | — | 1.6 | 0.0 | −0.5 | 0.5 |
| 50 | 4.1 | 10.0 | 1.7 | −0.4 | −0.6 | −0.3 | 0.1 | 0.6 | 2.1 | — | — | — | — | — | — | — | — | — | −0.1 | −0.6 | 0.0 |
| 55 | 4.0 | 9.6 | 1.0 | −1.1 | −1.2 | −0.6 | −0.1 | 0.4 | 2.0 | — | — | — | — | — | — | — | — | — | −0.2 | −0.8 | −0.4 |
| 60 | 3.9 | 9.3 | 0.3 | −1.8 | −1.6 | −0.8 | −0.2 | 0.4 | 1.9 | — | — | — | — | — | — | — | — | — | — | −0.9 | −0.7 |
| 65 | 3.8 | 9.0 | −0.1 | −2.3 | −1.9 | −1.0 | −0.3 | 0.4 | — | — | — | — | — | — | — | — | — | — | — | −1.0 | −0.8 |
| 70 | 3.7 | 8.8 | −0.6 | −2.7 | −2.2 | −1.1 | −0.3 | 0.4 | — | — | — | — | — | — | — | — | — | — | — | — | −1.0 |
| 75 | 3.7 | 8.7 | −1.0 | −3.1 | −2.5 | −1.2 | −0.3 | 0.4 | — | — | — | — | — | — | — | — | — | — | — | — | −1.1 |
| 80 | 3.6 | 8.6 | −1.2 | −3.4 | −2.7 | −1.2 | −0.3 | 0.4 | — | — | — | — | — | — | — | — | — | — | — | — | −1.1 |
| 85 | — | 8.5 | −1.4 | −3.7 | −2.8 | −1.2 | −0.3 | 0.5 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 90 | — | — | −1.4 | −3.8 | −2.9 | −1.2 | −0.2 | 0.5 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 95 | — | — | −1.4 | −3.9 | −3.0 | −1.1 | −0.2 | 0.5 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 100 | — | — | — | −4.0 | −3.0 | −1.1 | −0.2 | 0.5 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 105 | — | — | — | — | −3.0 | −1.1 | −0.1 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 110 | — | — | — | — | — | −1.1 | −0.1 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 115 | — | — | — | — | — | −1.1 | −0.1 | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 120 | — | — | — | — | — | −1.0 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| 125 | — | — | — | — | — | −1.0 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |

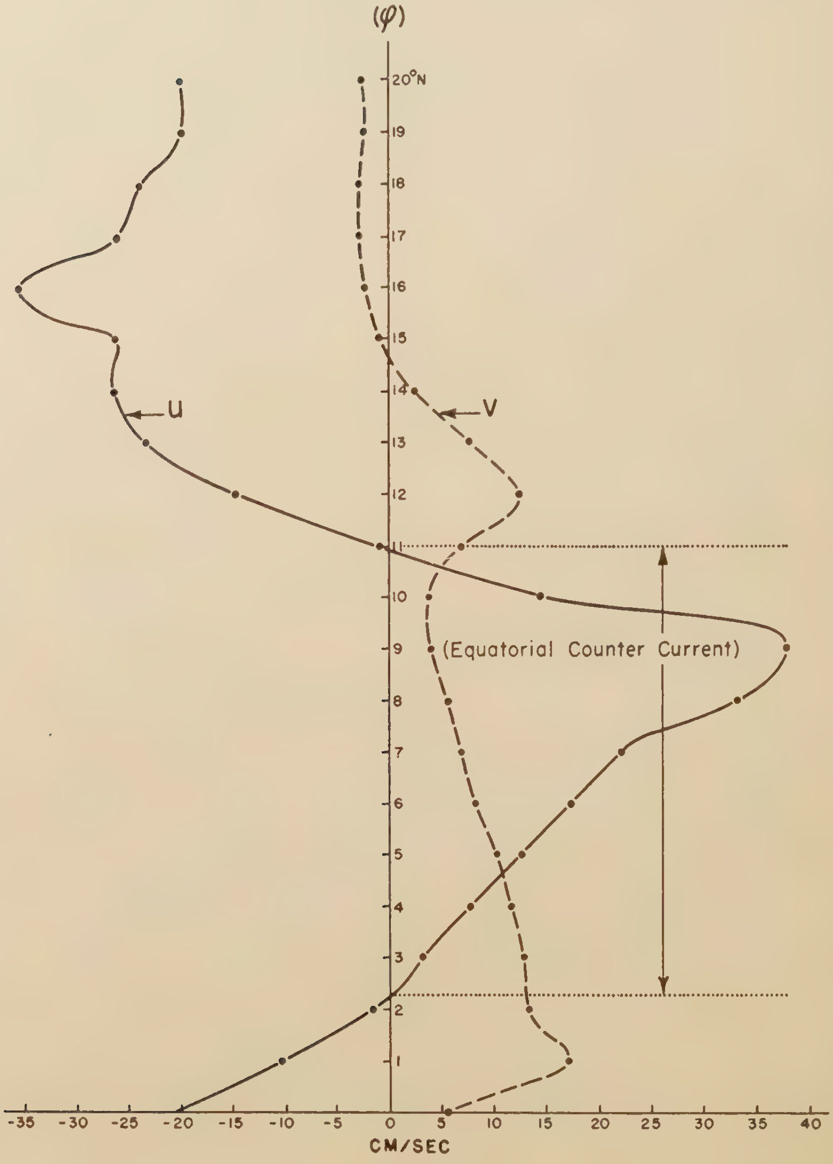


Figure 1a. Latitude dependence of the (horizontal) velocity components at surface.

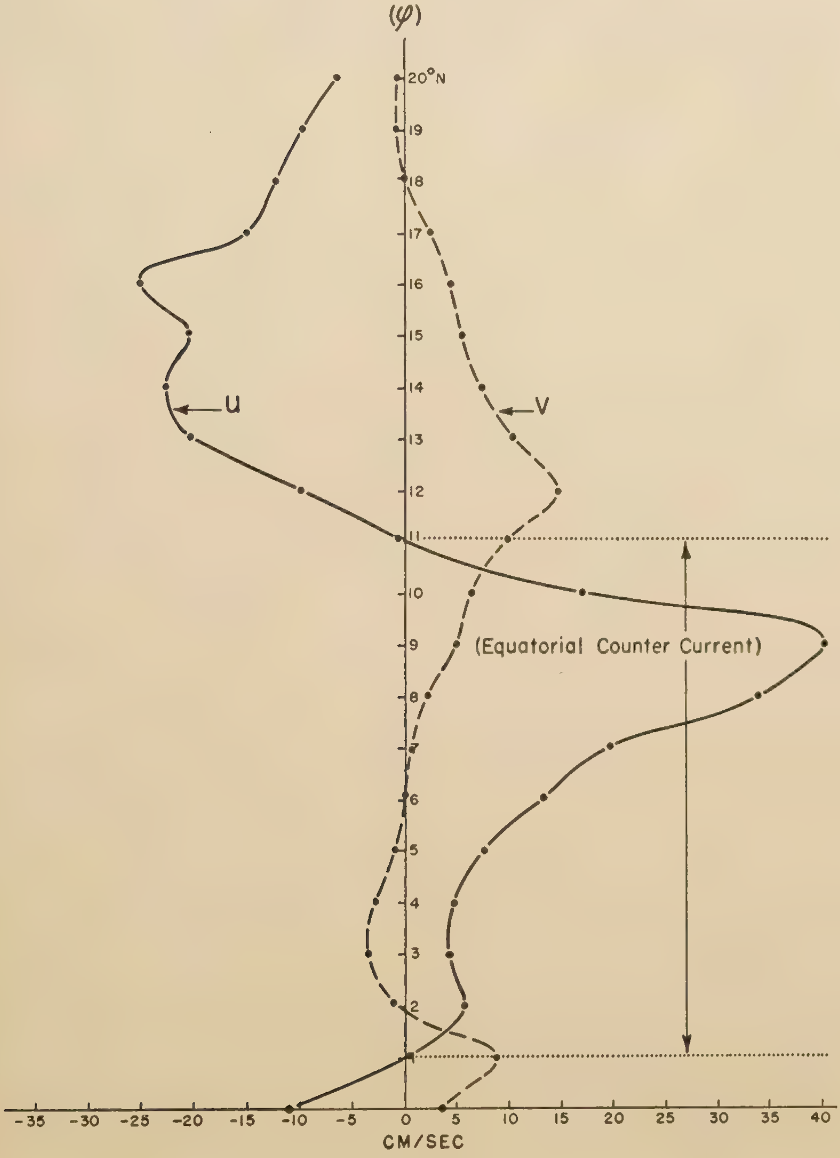


**Figure 1b.** Latitude dependence of the (horizontal) velocity components at boundary h.

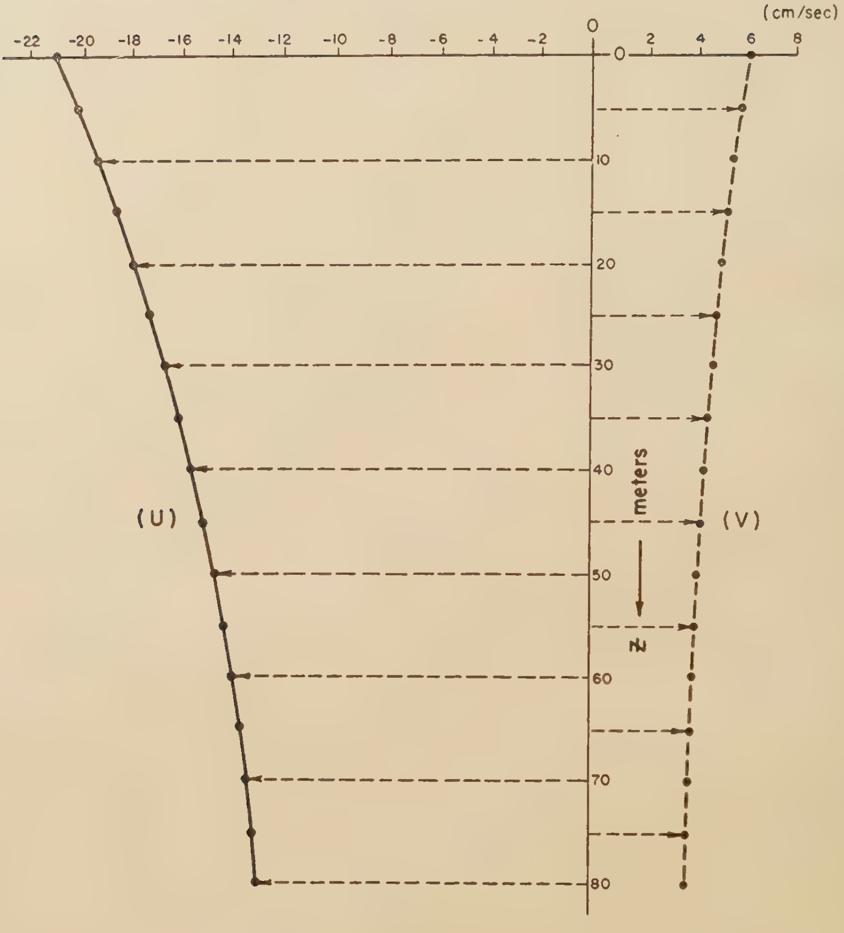


Figure 2a. Vertical profile of (horizontal) velocity components in the South Equatorial Current System (at equator).

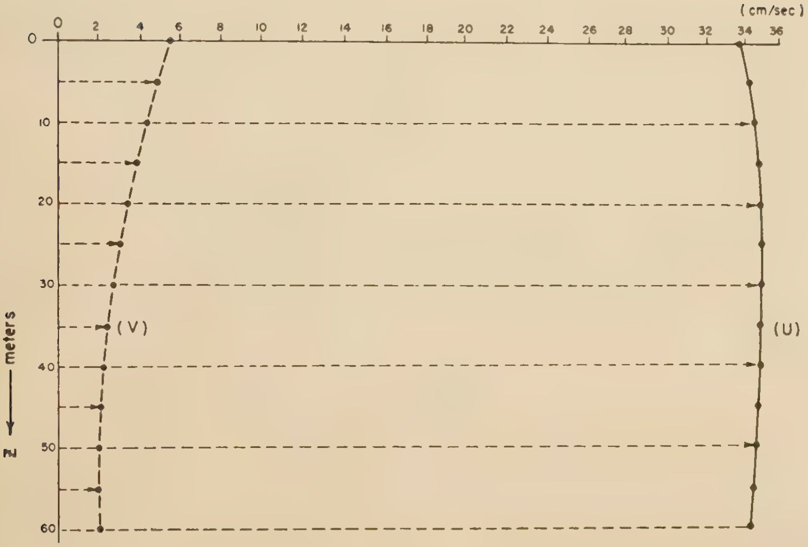


**Figure 2b.** Vertical profile of (horizontal) velocity components in the Equatorial Counter Current System (at 8° N).

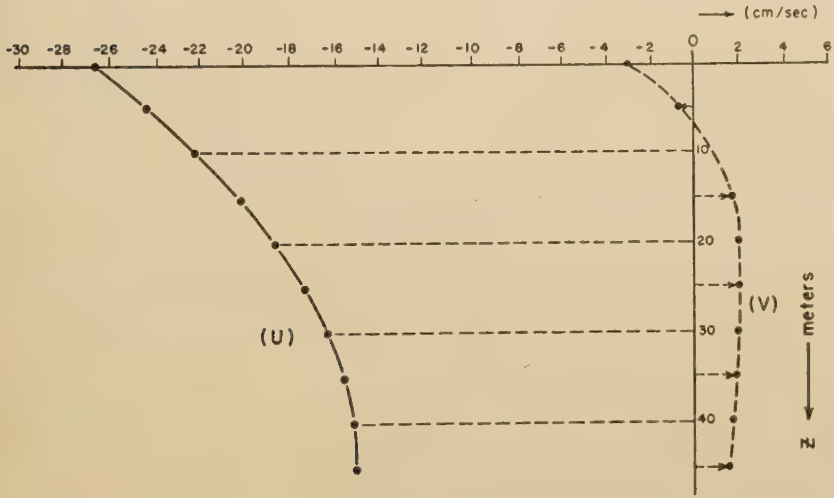


**Figure 2c.** Vertical profile of (horizontal) velocity components in the North Equatorial Current System (at 17° N).

## THEORY AND COMPUTATIONS OF VERTICAL MOTION

The vertical velocity in the upper mixed layer, derived from the integrated equation of continuity, is

$$w(z) = -\int_{-\zeta}^{z} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz\,, \tag{13}$$

provided that $w$ is vanishingly small along the sea surface ($z = -\zeta$). For the vertical velocity at $z = h$, we have

$$\begin{aligned} w(h) &= -\int_{-\zeta}^{h} \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) dz \\ &= -\left\{\frac{\partial}{\partial x}\int_{-\zeta}^{h} u dz + \frac{\partial}{\partial y}\int_{-\zeta}^{h} v dz\right\} \\ &\quad + u_h \frac{\partial h}{\partial x} + v_h \frac{\partial h}{\partial y}\,, \end{aligned} \tag{14}$$

provided that

$$u_\zeta \frac{\partial \zeta}{\partial x} \ll u_h \frac{\partial h}{\partial x}\,, \qquad v_\zeta \frac{\partial \zeta}{\partial y} \ll v_h \frac{\partial h}{\partial y}\,,$$

which are easily fulfilled.

From this equation it is seen that the divergence of mass transport is explicitly involved in the derivation of the vertical velocity, and thus it is desirable at this time to proceed somewhat further in the development of mass transport theory for both the upper homogeneous layer and the underlying layer. To avoid confusion, the following notations shall be adopted:

$$\begin{aligned} M_x &= \int_{-\zeta}^{d} \rho u dz\,, & M_y &= \int_{-\zeta}^{d} \rho v dz \text{ (for the whole layer)} \\ M_x' &= \int_{-\zeta}^{h} \rho u dz\,, & M_y' &= \int_{-\zeta}^{h} \rho v dz \text{ (for the upper homogeneous layer)} \\ M_x'' &= \int_{h}^{d} \rho u dz\,, & M_y'' &= \int_{h}^{d} \rho v dz \text{ (for the underlying layer),} \end{aligned} \tag{15}$$

where $d$ is depth of no motion.

Integrating the basic equation of motion (1) from the surface to depth of no motion, we obtain

$$\begin{aligned} M_x &= \frac{1}{\lambda^2 + k^2}\left[-(kf_1 + \lambda f_2) + k\tau_x + \lambda\tau_y\right] \\ M_y &= \frac{1}{\lambda^2 + k^2}\left[(\lambda f_1 - kf_2) + k\tau_y - \lambda\tau_x\right]. \end{aligned} \tag{16}$$

In a similar manner, the mass transport for the upper homogeneous layer, $M_x'$ and $M_y'$, is

$$\begin{aligned} M_x' &= \frac{1}{\lambda^2 + k^2}\left[-(kf_1' + \lambda f_2') + k\tau_x + \lambda\tau_y\right] \\ M_y' &= \frac{1}{\lambda^2 + k^2}\left[(\lambda f_1' - kf_2') + k\tau_y - \lambda\tau_x\right], \end{aligned} \qquad (17)$$

where $f_1' = \frac{\partial}{\partial x}\int_{-\zeta}^{h} pdz$ and $f_2' = \frac{\partial}{\partial y}\int_{-\zeta}^{h} pdz$ .

By use of the relations

$$f_1' = \frac{2}{5}f_1 \text{ and } f_2' = \frac{2}{5}f_2 , \qquad (18)$$

which are easily found from Reid's model of density distribution, we obtain

$$\begin{aligned} M_x' &= \frac{2}{5}M_x + \frac{3}{5}\frac{1}{\lambda^2 + k^2}(k\tau_x + \lambda\tau_y) \\ M_y' &= \frac{2}{5}M_y + \frac{3}{5}\frac{1}{\lambda^2 + k^2}(k\tau_y - \lambda\tau_x) \end{aligned} \qquad (19)$$

for the upper layer, and

$$\begin{aligned} M_x'' &= -\frac{3}{5}\frac{1}{\lambda^2 + k^2}(kf_1 + \lambda f_2) \\ M_y'' &= -\frac{3}{5}\frac{1}{\lambda^2 + k^2}(\lambda f_1 - kf_2) \end{aligned} \qquad (20)$$

for the underlying layer.

From equation (19) and the integrated equation of continuity for the whole water column,

$$\frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y} = 0 , \qquad (21)$$

we obtain

$$\frac{\partial M_x'}{\partial x} + \frac{\partial M_y'}{\partial y} = \frac{3}{5}\frac{\partial}{\partial y}\left[\frac{1}{\lambda^2 + k^2}(k\tau_y - \lambda\tau_x)\right], \qquad (22)$$

provided that $\tau_x$ and $\tau_y$ are functions of $y$ only.

By substituting equation (22) in equation (14) [the other quantities in the right-hand side of equation (14) are known], $w$ at $z = h$ can be determined.

An approximation of $w$ for $-\zeta \leq z \leq h$ is

$$w^*(z) = -\int_{-\zeta}^{z} \frac{\partial v}{\partial y}\,dz\,. \tag{23}$$

Therefore

$$\begin{aligned} w(h) &= w^*(h) - \int_{-\zeta}^{h} \frac{\partial u}{\partial x}\,dz \\ &= w^*(h) - \frac{\partial M_x'}{\partial x} + u_h \frac{\partial h}{\partial x} \\ &= w^*(h) + \frac{2}{5}\frac{\partial M_y}{\partial y} + u_h \frac{\partial h}{\partial x} \end{aligned} \tag{24}$$

if the relationship

$$\frac{\partial M_x'}{\partial x} = \frac{2}{5}\frac{\partial M_x}{\partial x} = -\frac{2}{5}\frac{\partial M_y}{\partial y}$$

is used.

Our results suggest that

$$\int_{-\zeta}^{z} \frac{\partial u_2}{\partial x}\,dz \ll \int_{-\zeta}^{z} \frac{\partial u_1}{\partial x}\,dz$$

and

$$\left| u_h \frac{\partial h}{\partial x} \right| \ll \left| \frac{2}{5}\frac{\partial M_y}{\partial y} \right|$$

so that the following approximation

$$-\int_{-\zeta}^{z} \frac{\partial u}{\partial x}\,dz \approx -\frac{\partial u_1}{\partial x}\,z \approx \frac{2}{5}\left(\frac{z}{h}\right)\frac{\partial M_y}{\partial y} \tag{25}$$

can be derived. Combining equations (13), (23) and (25), the expression for $w$ $(z)$ is given as

$$w(z) = w^*(z) + \left(\frac{z}{h}\right)\left(\frac{2}{5}\frac{\partial M_y}{\partial y}\right). \tag{26}$$

TABLE II—DISTRIBUTION OF VERTICAL COMPONENT ($w$) OF CURRENT VELOCITY IN THE EQUATORIAL NORTH PACIFIC (IN $10^{-3}$ CM/SEC)

| Depth (m) | LATITUDE (°) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 0 | | | | | | | | | | | | | | | | | | | | | |
| 5 | −.43 | .00 | .01 | .07 | .09 | .11 | .08 | .07 | .04 | −.01 | −.16 | −.23 | .19 | .15 | .11 | .08 | .01 | −.01 | −.02 | .01 | |
| 10 | −.69 | −.13 | .04 | .16 | .18 | .21 | .15 | .11 | .02 | −.07 | −.35 | −.39 | .32 | .19 | .16 | .15 | .01 | −.04 | −.05 | .01 | |
| 15 | −.97 | −.29 | .08 | .25 | .26 | .30 | .21 | .12 | −.02 | −.17 | −.53 | −.54 | .44 | .23 | .19 | .21 | .03 | −.06 | −.07 | −.02 | |
| 20 | −1.20 | −.37 | .14 | .34 | .33 | .38 | .25 | .11 | −.09 | −.28 | −.71 | — | — | .26 | .21 | .26 | .06 | −.08 | −.08 | −.04 | |
| 25 | −1.40 | −.46 | .19 | .43 | .39 | .44 | .27 | .09 | −.18 | −.40 | −.80 | — | — | — | .23 | .32 | .09 | −.08 | −.09 | −.08 | |
| 30 | −1.55 | −.53 | .24 | .50 | .44 | .49 | .30 | .06 | −.29 | −.53 | — | — | — | — | — | .37 | .14 | −.07 | −.09 | −.13 | |
| 35 | −1.69 | −.57 | .30 | .57 | .49 | .54 | .32 | .01 | −.40 | −.59 | — | — | — | — | — | .40 | .21 | −.05 | −.09 | −.15 | |
| 40 | −1.79 | −.56 | .36 | .64 | .52 | .58 | .33 | −.03 | −.53 | — | — | — | — | — | — | — | .28 | −.02 | −.09 | −.26 | |
| 45 | −1.88 | −.55 | .44 | .68 | .55 | .59 | .31 | −.08 | −.66 | — | — | — | — | — | — | — | .31 | .03 | −.08 | −.29 | |
| 50 | −1.95 | −.49 | .52 | .72 | .56 | .59 | .31 | −.16 | −.81 | — | — | — | — | — | — | — | — | .10 | −.06 | −.20 | |
| 55 | −2.01 | −.47 | .59 | .76 | .56 | .58 | .30 | −.22 | — | — | — | — | — | — | — | — | — | .11 | −.02 | −.18 | |
| 60 | −2.05 | −.41 | .67 | .78 | .54 | .57 | .28 | −.27 | — | — | — | — | — | — | — | — | — | — | −.02 | −.16 | |
| 65 | −2.10 | −.35 | .75 | .79 | .53 | .56 | .26 | −.34 | — | — | — | — | — | — | — | — | — | — | — | −.15 | |
| 70 | −2.16 | −.27 | .84 | .79 | .50 | .54 | .24 | −.43 | — | — | — | — | — | — | — | — | — | — | — | — | |
| 75 | −2.23 | −.19 | .90 | .79 | .46 | .51 | .22 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 80 | −2.26 | −.12 | .98 | .78 | .40 | .48 | .19 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 85 | −2.30 | .01 | 1.05 | .77 | .35 | .45 | .16 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 90 | — | .15 | 1.14 | .75 | .30 | .43 | .14 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 95 | — | — | 1.22 | .73 | .24 | .41 | .12 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 100 | — | — | 1.32 | .70 | .17 | .38 | .09 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 105 | — | — | — | .68 | .09 | .35 | .06 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 110 | — | — | — | — | .02 | .32 | .03 | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 115 | — | — | — | — | −.04 | .30 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | |
| 120 | — | — | — | — | — | .26 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | |

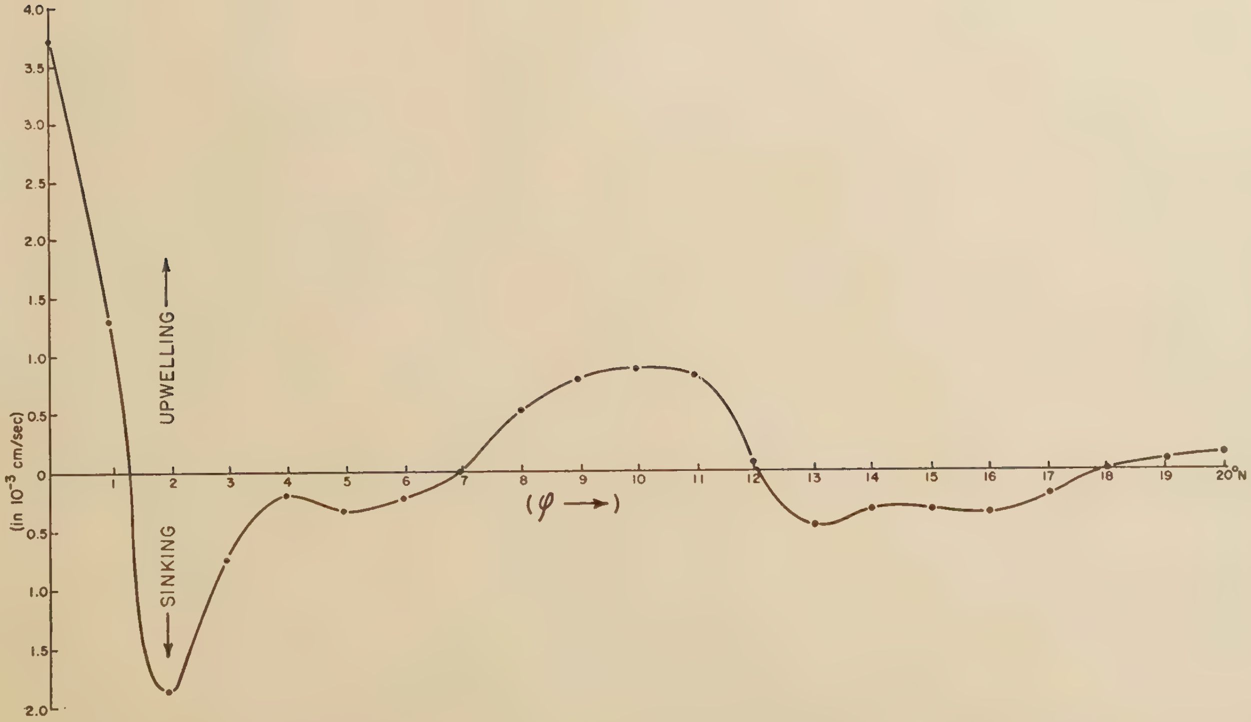
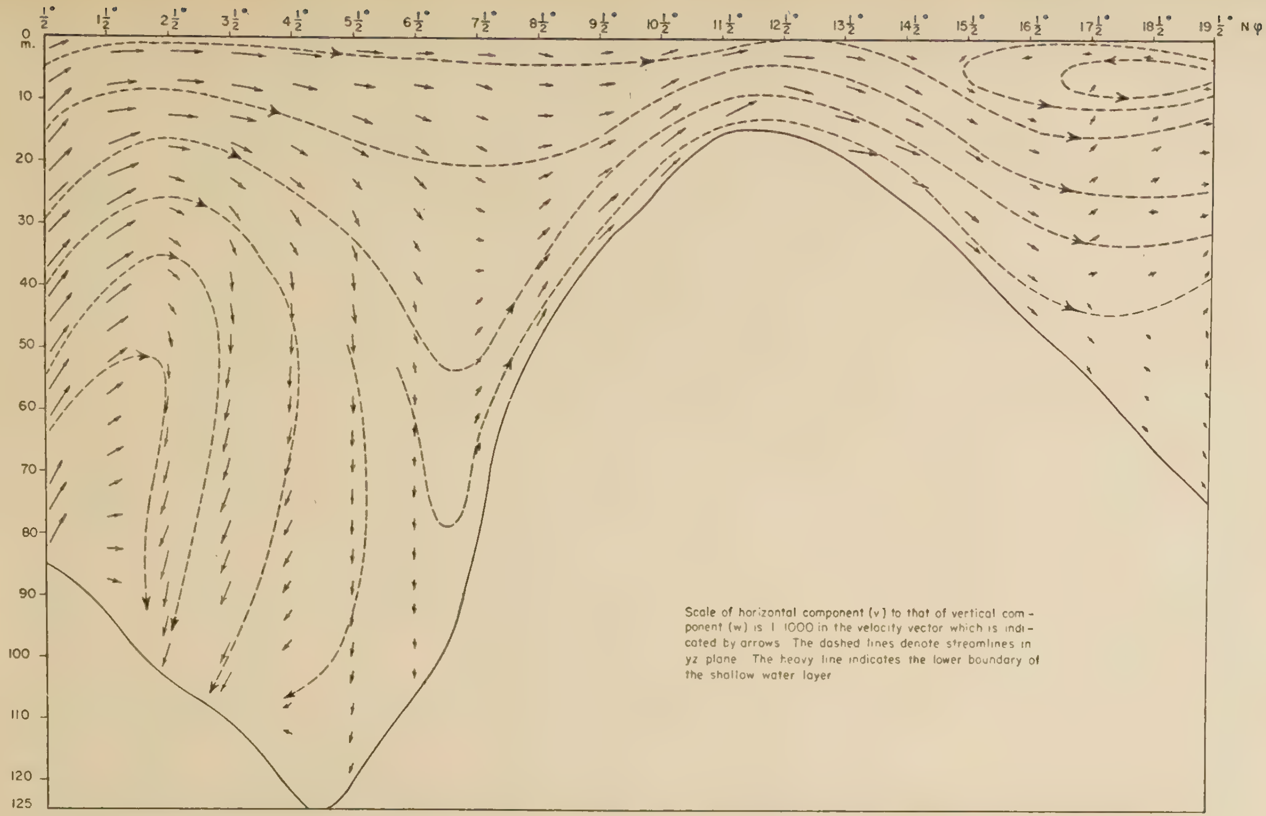


Figure 3. Latitude dependence of the vertical motion at the lower boundary of the shallow water layer h.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125

Scale of horizontal component (v) to that of vertical component (w) is 1 1000 in the velocity vector which is indicated by arrows The dashed lines denote streamlines in yz plane The heavy line indicates the lower boundary of the shallow water layer

Figure 4. Representation of shallow water circulation in a vertical plane along the North-South direction.

The numerical results of $w$ integrated vertically for increments of 5 meters are tabulated in Table II. The vertical velocity at depth $z = h$ for various latitudes is given in Fig. 3. Combining the corresponding values of $v$ and $w$ from Tables IB and II, we obtain a picture of the velocity field in a vertical plane as shown in Fig. 4.

## CONCLUSIONS

Based on the results of previous sections, the general features of the velocity field in the equatorial area of the North Pacific may be described. The boundaries of the Equatorial Counter Current are located at about 2½° N and 11° N at the surface of the upper mixed layer and at approximately 1° N and 11° N at the bottom of the upper mixed layer. The locations of the surface boundaries agree satisfactorily with most observational data available. Our results suggest that the southern boundary is inclined to the south with increasing depth, thus conforming to the widening of the Counter Current with depth as indicated by the Carnegie profile (Sverdrup, et al., 1946: 710, fig. 198). Preliminary results of the recent Shellback Expedition (Wooster, 1952) in the eastern equatorial North Pacific suggest that portions of the Counter Current underlie the Equatorial Current.

The maximum horizontal velocity in the Equatorial Counter Current system, calculated from equations derived in the present study, is somewhat over 40 cm/sec at the surface. This agrees well in magnitude with the computed results of the Carnegie data, with current meter observations by Japanese investigations (Japanese Hydrographic Department, 1933) and with recent geomagnetic electrokinetograph (GEK) observations made on Shellback. Values of the drag coefficient of the wind stress used herein, adopted from Sverdrup (1947), Munk (1947), and Reid (1948a), are in disagreement with the values obtained by Neumann (1948) and Weenink and Groen (1952). Except at the boundary zones between the different current systems, the zonal component ($u$) of the surface flow is always much larger than its meridional component ($v$), and it is especially so at some distance within each of the major current systems (Figs. 1a and 1b). Recently, the U. S. Fish and Wildlife Service (1952) reported that the surface flow of the Equatorial Counter Current was almost entirely from west to east and that there was no appreciable north-south component.

The typical vertical profiles of the horizontal velocity within each of the three major current systems in the equatorial area differ considerably (Figs. 2a to 2c). The Counter Current system is distinctive in that horizontal velocities are virtually constant with depth in the stirred layer. (Shellback Expedition data confirm this result.)

This is due to the predominant role played by the "gradient current" (which is independent of depth in the homogeneous layer) in the Counter Current area where the wind stress is very small.

The numerical results of the distribution of the vertical velocity found in this study are reasonable; the main features are: (1) Very strong upwelling at and near the equator (equatorial divergence); (2) strong sinking at the southern boundary of the Counter Current (note the subsurface convergence in Fig. 4); and (3) fairly strong upwelling at the northern boundary of the Counter Current. The order of magnitude of vertical velocity is from $10^{-4}$ to $10^{-3}$ cm/sec. This corresponds closely to values found off the California Coast by McEwen (1919).

## DISCUSSION

In this study extensive use has been made of Reid's value of $h$ in the numerical computations. It is to be noted that, in Reid's model, lateral mixing is neglected, while in the present study it is included. Fortunately numerical computations show that, for a high value of the lateral mixing coefficient (that is, $10^8$ cgs for $B$ in our notation), the effect of lateral mixing is negligible except very near the equator. Therefore, at higher latitudes Reid's model values of $h$ are sufficiently accurate for use in this study. However, in the very low latitudes, where lateral mixing may be important, values of $h$ have been taken from actual observed data (Sverdrup, et al., 1944).

Substitution of $-ku$ and $-kv$ for the lateral mixing terms permitted mathematical simplification. This should be a close first approximation when the velocity distribution is essentially sinusoidal along the $y$-coordinate, which is very close to the actual case within the area considered. The horizontal distribution of $v$ (Figs. 1a and 1b) which was obtained from our results departs somewhat from a sinusoidal pattern which we assumed in introducing the lateral-mixing effect. However, it can be seen from equation (1) that deviation from a perfect sinusoidal curve would not materially alter our results.

Assignment of values for the parameter $k$ is based mainly on reasonable values of the wave length ($L$) of the sinusoidal velocity distribution as well as that of the coefficient of lateral mixing ($B$) (Montgomery, et al., 1940; Sverdrup, et al., 1946: 485). Since it is generally thought that the curvature of the horizontal current profile (cf. Fig. 1a) is comparatively large very near the equator, which means that the wave length of the sinusoidal velocity distribution is smaller, larger values of the parameter $k$ should be employed in the vicinity of the equator.

Our approach differs considerably from that by Defant (1936). First, in Defant's work, surface values of $v$ are preassigned, while in ours they are determined from consideration of the mean distribution of wind stress. Second, in Defant's work, the N-S component of surface flow is always in reverse directions to that of subsurface flow as a result of his assumption of $M_y = 0$ in a vertical plane; this is considered rather arbitrary and is avoided in our work. Third, Defant's result shows that the current always follows the lower boundary surface of the homogeneous layer (at $z = h$); however, our results demonstrate that it is not necessarily true. It has been shown in equation (14) that the flow does not follow the inclined surface of the lower boundary if the divergence of mass transport in the upper mixed layer does not vanish, and this proves to be the case in low latitudes (below 7° N). Fourth, obvious divergence or convergence at the boundaries of the three major current systems, as shown in Defant's result, does not appear in our picture except for the subsurface divergence at the southern boundary of the Counter Current. Direct measurements of the current at the surface and subsurface levels (especially at the boundaries of the major current systems) will test these two models.

Papers by Weenink and Groen (1952) and Kajiura (1952), which share common interest with our study, have been published recently. One of the essential differences between their works and ours is that they assume the coefficient of vertical eddy viscosity to be constant for the whole water column while we have adopted a discontinuous function at $z = h$. The merits of this assumption are twofold. First, it takes into consideration the fact that the momentum transfer due to turbulent motion is largely reduced where vertical stability is high. This is the case at $z = h$, as is shown in Reid's model of the density distribution. Second, the circulation in the upper stirred layer can be treated semi-independently of the underlying circulation, thus facilitating a simpler mathematical solution. The circulation in the upper layer depends upon the distribution of $h$, which may be affected in turn by motion in the underlying mass.

Although Weenink and Groen's work is concerned only with the surface current while Kajiura's work included discussions of subsurface current, their approximate solutions are identical. Such solution is based on the assumption that $1 \ll h\sqrt{\frac{\lambda\rho}{2A}}$. It can be shown numerically that, if $A$ is assumed to be $10^2$, as used by Kajiura, the approximate solution deviates about 10 to 25 % from the exact one in the area between 9° N and 15° N, where $h\sqrt{\frac{\lambda\rho}{2A}}$ is not large. At the equator itself and its vicinity, both Weenink and Groen's solution and ours are finite by different approaches; the fitness of the two requires further investigation. In Kajiura's work, the proximity of the equator was excluded.

It is interesting to note that there are certain discrepancies between our result and the direct measurements on SHELLBACK in the latitudinal variation of the horizontal velocity; GEK measurements did not detect the North Equatorial Current but gave current velocities commonly as high as about 1 knot (50 cm/sec) on the northern boundary of the South Equatorial Current (Wooster, 1952). In Fig. IA it is immediately seen that at the northern limit of the Counter Current the velocity shear is large and the width of the horizontal boundary zone narrow while at its southern limit the opposite is the case. These discrepancies probably can be explained largely as a result of the near coastal location of SHELLBACK observations and of other variations in the velocity field that might be expected at a greater distance from land (Robinson, 1952). The large velocity shear at the northern boundary of the Counter Current might possibly lead to the meandering of the Current which might eventually cause the formation of the "large-scale" eddies which have been noted by the SHELLBACK Expedition and which have been borne out by the CROSSROADS data (Barnes, et al., 1948). Such velocity shear and eddies will be considered further in our next work.

## REFERENCES

BARNES, C. A., D. R. BUMPUS AND JOHN LYMAN
1948. Ocean circulation in the Marshall Islands area. Trans. Amer. geophys. Un. *29:* 871–876.

DEFANT, ALBERT
1936. Schichtung und Zirkulation der Atlantischen Ozeans. Die Troposphäre. Wiss. Ergebn. dtsch. Atlant. Exped., *6* (3): 316–326.

HIDAKA, KOJI
1951. Drift currents in an enclosed ocean. Part III. Geophys. Notes, Geophys. Inst., Tokyo Univ., *4* (3): 1–19.

HIDAKA, KOJI AND KENZO TAKANO
1952. Wind-driven current and lateral mixing in a zonal ocean. Geophys. Mag., Tokyo, *23* (4): 487–495.

HIDAKA, KOJI, AND TEIICHIRO KUSUNOKI
1951. On the mixing coefficient and the meridional component of velocity in the Equatorial Counter Current. J. Oceanogr. Soc. Japan, *6:* 168–173.

JAPANESE HYDROGRAPHIC DEPARTMENT
1933. Bulletin of the Hydrographic Department of the Imperial Japanese Navy, *6:* 187–211.

KAJIURA, KINJIRO
1952. The velocity distribution of wind currents in the eastern part of the equatorial Pacific. J. Oceanogr. Soc. Japan, *8:* 15–22.

McEwen, G. F.
1919. Ocean temperatures, their relation to solar radiation and oceanic circulation. Semicentennial Publ. Univ. Calif., 1868–1918: 335–421.
Montgomery, R. B., and E. Palmen
1940. Contribution to the question of the Equatorial Counter Current. J. Mar. Res., *3:* 112–133.
Munk, W. H.
1947. A critical wind speed for air-sea boundary processes. J. Mar. Res., *6:* 203–218.
1950. On the wind-driven oceanic circulation. J. Meteorol., *7:* 79–93.
Munk, W. H., and E. R. Anderson
1948. Notes on a theory of the thermocline. J. Mar. Res., *7:* 276–295.
Neumann, Gerhard
1948. Uber den Tangentialdruck des Windes und die Rauhigkeit der Meeresoberflache. Z. Meteorol., *2:* 193-203.
Reid, R. O.
1948a. The equatorial currents of the eastern Pacific as maintained by the stress of the wind. J. Mar. Res., *7:* 74–99.
1948b. A model of the vertical structure of mass in equatorial wind-driven currents of a baroclinic ocean. J. Mar. Res., *7:* 304–312.
Robinson, M. K.
1952. Sea temperature in the Marshall Islands area, 20° N–5° S., 155° E–175° W. SIO Reference, 52–45 (unpublished).
Stockmann, W. B.
1946a. A theory of equatorial currents in the ocean. C. R. Acad. Sci. URSS., *52:* 309–312.
1946b. Equation for a field of total flow induced by wind in a non-homogeneous sea. C. R. Acad. Sci. URSS., *54:* 403–406.
Stommel, Henry
1948. The westward intensification of wind-driven ocean currents. Trans. Amer. geophys. Un., *29:* 202–206.
Sverdrup, H. U.
1947. Wind-driven currents in a baroclinic ocean; with application to the equatorial currents of the eastern Pacific. Proc. nat. Acad. Sci., *33:* 318–326.
Sverdrup, H. U. and J. A. Fleming.
1944. Scientific results of cruise VII of the CARNEGIE, 1928–29. Oceanography I–A. Observations and results in physical oceanography II. Results in physical oceanography. Publ. Carnegie Inst., 545: 83–148.
Sverdrup, H. U., M. W. Johnson and R. H. Fleming.
1946. The oceans. Prentice-Hall Inc., New York. 2nd ed., 1087 pp. (pp. 484 and 710).
U. S. Fish and Wildlife Service
1952. Pacific Oceanic Fishery Investigation, Cruise Report, Cruise 16.
Weenink, M. P. H. and Pier Groen.
1952. On the computation of oceanic surface current velocities in the equatorial region from wind data. Koninkl. Nederl. Akad. Weten., Proc., (B) 55: 239.
Wooster, W. S.
1952. Preliminary report, Shellback Expedition, 17 May to 28 August 1952. SIO Reference 52–47 (unpublished).

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# 9. The Propagation of Gravity Waves from Deep to Shallow Water

By Carl Eckart[1]

he Laplace equation, together with the appropriate boundary conditions at the surface and the rigid bottom (of variable depth $h(x,y)$ beneath the undisturbed ace), is transformed into an integro-differential equation. This is shown to be roximated by the partial differential equation

$$\frac{1}{\mu}\left\{\frac{\partial}{\partial x}\left(\mu\frac{\partial p_0}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial p_0}{\partial y}\right)\right\}+k^2p_0=0,$$

re $p_0/\rho g$ is the surface displacement and $\mu=1-\exp(-2\kappa h)$, $k^2=\kappa^2 \operatorname{ctnh}(\kappa h)$, $^2/g$, $\omega$=frequency, radians per second, $g$=acceleration of gravity, $\rho$=density of the .

can be shown that the above expression for the wave-number $k$ differs from the monly accepted value, which is the root of the equation $\kappa=k \tanh(kh)$, by less than rcent for any value of $kh$; and, for both large and small values, by considerably less. he integro-differential equation also leads to a series for the pressure at any depth erms of $p_0$ and its derivatives. The excess pressure at the bottom, when calculated the first two terms of this series, is

$$p(-h)=p_0\,[1-\exp(-\kappa h)]/\sinh(\kappa h).$$

is independent of $x$ and $y$, the exact expression is known to be $p(-h)=p_0/\cosh(kh)$. difference between these two expressions is again less than 5 percent for any value $h$, and approaches zero for both large and small values of $kh$.

hen $h=sx$ (plane bottom of constant slope), the wave equation given above can olved in terms of hypergeometric functions. This solution yields an analytic ession for the increase in height when the waves travel from very deep water into low water: a wave of unit amplitude in deep water, and of angle of incidence $\theta$, eases to the height $H=(\frac{1}{2}\cos\theta)^{\frac{1}{2}}/(\kappa h)^{\frac{1}{4}}$ for small values of $\kappa h$. The factor 1/2 is ily identified as being the ratio of the group and phase velocities in deep water.

## 1. Introduction

he propagation of gravity waves on the surface of an incompressible involves a nonlinear boundary condition at the free surface. It is omary to simplify the problem by neglecting the nonlinear terms in boundary equation, as well as in the Eulerian equations, and this will one in the following also.

his linearized problem has been solved exactly only for the case of ane bottom: these calculations for a horizontal plane are given by b [1, Chap. IX][2] and an extensive treatment of the sloping plane ether with references to the relevant literature) has recently been n by Stoker. [2] More frequently, the problem is further simplified upposing (1) that the water's depth is everywhere small compared to wave length,[3] and (2) that the slope of the bottom, while not constant,

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ripps Institution of Oceanography, University of California, La Jolla, Calif.
gures in brackets indicate the literature references on p. 173
rictly, small compared to the length that the waves would have if they were propagated on the of very deep water; for simplicity, this is called the "deep-water wave length."

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is everywhere small. The basic equations of this "shallow-water the together with their solutions for a few special cases, are given by L [1, Chap. VII, p. 291]

It appears that it is possible to generalize the equations of the sha water theory so that it applies equally well to water of any depth. ever, the assumption that the bottom slope is small enough to be negli must be retained, and certain other terms must also be neglected. I not been possible to formulate the necessary and sufficient condi under which these approximations are justifiable, but various tests been applied to the approximate equations, and these lead one to reasonable confidence in them.

Since these approximate equations can be treated more readily (b WKB and numerical methods if necessary) than can those of the linearized theory, they are useful in certain applications. Moreover methods employed in deriving them can also be used to obtain app mate solutions of other boundary-value problems.

## 2. Derivation of the Equations

Let the positive $z$-axis be vertically upward and the undisturbe surface at $z=0$. Let the pressure be $-\rho gz+p(x,y,z,t)$, where $\rho$ i density of the fluid and $g$ the acceleration of free fall. If the pre over the fluid be zero, the linearized equation of the free surface w

$$\rho gz=p(x,y,0,t)=p_0(x,y,t).$$

The free surface must also move with the fluid; to the same linea approximation, this results in the boundary condition

$$g\frac{\partial p}{\partial z}+\frac{\partial^2 p}{\partial t^2}=0, \quad \text{when} \quad z=0.$$

If the wave motion is simply harmonic, with period $2\pi/\omega$, eq 2 m written

$$\frac{\partial p}{\partial z}=\omega^2 p/g=\kappa p, \quad \text{when} \quad z=0.$$

where $2\pi/\kappa$ is the deep-water wave length.

If the equation of the bottom is

$$z=-h(x,y)$$

and it is impermeable, the remaining boundary condition is [4]

$$\frac{\partial p}{\partial x}\frac{\partial h}{\partial x}+\frac{\partial p}{\partial y}\frac{\partial h}{\partial y}+\frac{\partial p}{\partial z}=0, \quad \text{when} \quad z=-h.$$

---

[4] It is difficult to justify the inclusion of the terms in $\partial h/\partial x$, $\partial h/\partial y$ in eq 4 without also presentin ments against the linearized eq 1 and 2. However, the omission of these terms from eq 4 yield that are demonstrably false. The inclusion of the analogous terms in eq 1 and 2 yield nonlinear e that cannot easily be solved. These matters will not be discussed further, but are mentioned here they present problems that need clarification.

lly, the function $p$ must satisfy Laplace's equation

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}=0. \tag{5}$$

present problem is the approximate solution of these equations. will be necessary to consider the values of $p$ at two different levels, d $\zeta$, and to introduce the auxiliary function

$$g(\zeta,z)=(1/\kappa)\sinh\kappa(\zeta-z), \tag{6}$$

h satisfies the differential equation

$$\frac{\partial^2 g}{\partial \zeta^2}=\kappa^2 g. \tag{7}$$

ation 5 may be rewritten

$$\frac{\partial^2 p}{\partial \zeta^2}=-\Delta p, \tag{5a}$$

e

$$\Delta=(\partial/\partial x)^2+(\partial/\partial y)^2.$$

ultiplying eq 7 by $p(\zeta)$, eq 5a by $g$ and subtracting, one obtains

$$\frac{\partial}{\partial \zeta}\left[p(\zeta)\frac{\partial g}{\partial \zeta}-g\frac{\partial p(\zeta)}{\partial \zeta}\right]=g\left[\Delta p(\zeta)+\kappa^2 p(\zeta)\right].$$

ntegrating this from $\zeta=0$ to $z$, the result is

$$(z)-p(0)\cosh\kappa z-\frac{1}{\kappa}\left(\frac{\partial p}{\partial \zeta}\right)_{\zeta=0}\sinh\kappa z=\int_{\zeta=0}^{z} g(\zeta,z)[\Delta+\kappa^2]p(\zeta)d\zeta. \tag{8}$$

ing eq 2a, this becomes

$$p(z)=p_0\exp(\kappa z)+\frac{1}{\kappa}\int_{\zeta=0}^{z}\sinh\kappa(\zeta-z)[\Delta+\kappa^2]p(\zeta)d\zeta, \tag{9}$$

h is an integro-differential equation that is in all respects equivalent e two equations, eq 5 and eq 2a. If the function $p_0(x,y)$ is known, determines the function $p(x,y,z)$ uniquely. It therefore remains to mine $p_0$ so that eq 4 is satisfied.

fore proceeding to this, we note that

$$\kappa\sinh\kappa(\zeta-z)d\zeta=d[\cosh\kappa(\zeta-z)-1],$$

at eq 9 may be transformed by partial integration into

$$(z)=p_0\exp(\kappa z)+(1/\kappa^2)[1-\cosh\kappa z][\Delta p_0+\kappa^2 p_0]$$
$$+\frac{1}{\kappa^2}\int_0^z[1-\cosh\kappa(\zeta-z)][\Delta+\kappa^2]\frac{\partial p(\zeta)}{\partial \zeta}d\zeta. \tag{9a}$$

r some circumstances, the value of the integral will be small com- to the values of the other two terms in eq 9a; then an approximate solution is obtained by simply ignoring the integral. Without exam the justification for this approximation, it will be adopted throu the following.

If this approximate value of $p$ is substituted into eq 4, the result

$$0=\exp(-\kappa h)\left\{\frac{\partial p_0}{\partial x}\frac{\partial h}{\partial x}+\frac{\partial p_0}{\partial y}\frac{\partial h}{\partial y}+\kappa p_0\right\}+(1/\kappa)\sinh \kappa h\left\{\Delta p_0+\kappa^2 p_0\right\}+\ldots,$$

where the dots indicate terms involving third derivatives of $h$, etc.; will be neglected.[5]

The approximate eq 10 determines $p_0(x,y)$, and hence complete determination of $p(x,y,z)$. It may be written more systematica the wave equation

$$\frac{1}{\mu}\left\{\frac{\partial}{\partial x}\left(\mu\frac{\partial p_0}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial p_0}{\partial y}\right)\right\}+k^2 p_0=0,$$

where

$$\mu=1-\exp\,(-2\kappa h),$$

$$k^2=\kappa^2\,\mathrm{ctnh}\,(\kappa h).$$

## 3. Some Tests of the Validity of the Approximat

As a first test of the validity of these results, one may recover the equation for very shallow water. If $\kappa h \ll 1$,

$$\mu\rightarrow 2\kappa h,\quad k^2\rightarrow \omega^2/gh,$$

and eq 11 becomes

$$\frac{\partial}{\partial x}\left(h\frac{\partial p_0}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\frac{\partial p_0}{\partial y}\right)+\omega^2 p_0/g=0,$$

which has long been accepted as correct in this limiting case. [1, VII, p. 291]

As a second test, let $h$ be constant; a rigorous solution is known 364] to be

$$p_0=A\cos\,(kx-\omega t),$$

where $A$ is a constant of integration, and $k$ is the root of the transcen equation

$$\kappa=k\tanh\,(kh).$$

Since $\mu$ is constant in this case, eq 11 also has a solution of this but $k$ is determined by eq 13 and not by eq 15. The great formal ence between the two is misleading, as is shown in figure 1; the sol of this figure is the graph of eq 15, while the circles represent valu calculated from eq 13. The agreement between the two is very factory, even when $kh\sim 1$, and is extremely close for both larg smaller values.

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[5] An alternative derivation can be given by substituting the rigorous eq 9 into eq 4, then integ parts and neglecting the integral. The terms indicated by dots in eq 10 are then absorbed in th and disappear with it. While this is more systematic, it is also more elaborate, and no easier than is the derivation here given.

One may also use the simplified eq 9a to calculate the pressure on the ttom, and compare the result with that deduced from the known gorous solutions. Equation 9a yields

$$p(-h)=p_0[1-\exp(-\kappa h)]/\sinh \kappa h, \tag{16}$$

ile the rigorous value of this ratio is

$$p(-h)=p_0/\cosh kh. \tag{17}$$

ese two equations are compared numerically in figure 2, and again, the mparison is satisfactory.

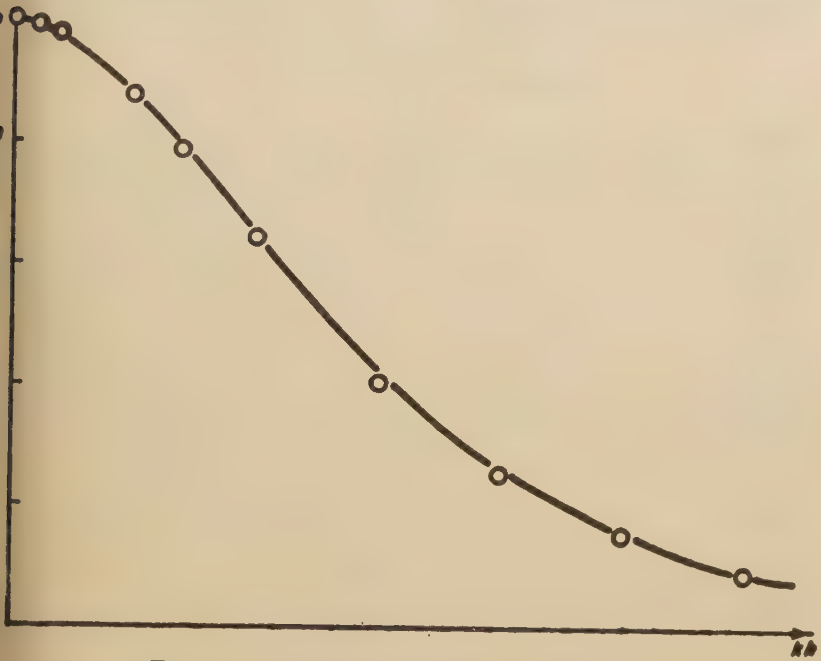

FIGURE 1. *Comparison of equations 13 and 15.*

—, $p(-h)/p_0=1/\cosh kh$

O, $p(-h)/p_0=(1-e^{-kh})/\sinh kh$

## 4. Solution of the Equation for a Bottom of Constant Slope

the bottom has a constant slope, eq 11 can be solved in terms of the ergeometric function. In this case

$$h=sx \tag{18}$$

ing the slope of the plane bottom. The introduction of a new inde- ent variable

$$\xi=\exp(-2\kappa h) \tag{19}$$

lts in

$$\mu=1-\xi, \quad k^2=\kappa^2(1+\xi)/(1-\xi). \tag{20}$$

The eq 11 is separable in this case, so that there are solutions of th

$$p_0(x,y)=q(\xi)\exp(iby),$$

where $b=\kappa\sin\theta$ is a constant, and $\theta$ is the angle of incidence of the before refraction in the shoaling water. The function $q$ satisfi hypergeometric equation

$$\xi\frac{d}{d\xi}\left[\xi(1-\xi)\frac{dq}{d\xi}\right]+\left[(\kappa^2-b^2)-(\kappa^2+b^2)\xi\right]q/4\kappa^2s^2=0.$$

The abbreviations

$$\left.\begin{aligned}\alpha^2&=(b^2-\kappa^2)/4\kappa^2s^2=-\cos^2\theta/4s^2\\ \beta^2&=[b^2+\kappa^2(1+s^2)]/4\kappa^2s^2\end{aligned}\right\}$$

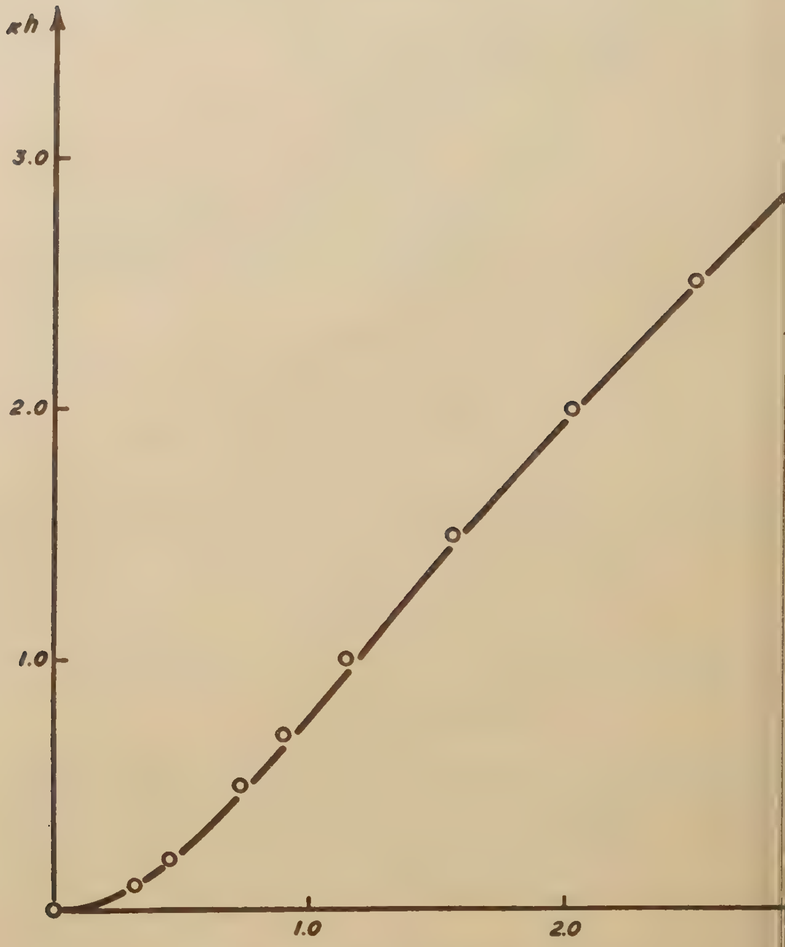

FIGURE 2. *Comparison of equations 16 and 17.*

—, $kh=kh\tanh kh$

○, $k^2h^2/\tanh kh=k^2h^2$

re convenient, and it is readily found that two solutions of eq 22 are

$$q_{\pm}=\xi^{\pm\alpha}F\left(\pm\alpha+\beta+\frac{1}{2},\ \pm\alpha-\beta+\frac{1}{2},\ 2\alpha+1,\xi\right), \tag{24}$$

here $F$ is the hypergeometric series [3] [4, Chap. VI] [5, Chap. IV, No. 7, hap. XVII] [6, Chap. II.].

$$F(l,m,n,x)=1+\frac{lm}{1\cdot n}x+\frac{l(l+1)m(m+1)}{1\cdot 2\cdot n(n+1)}x^2+\ldots.$$

It is to be noted that, for large positive values of $x$ (deep water), $\xi$ is ery small, and the approximation

$$q_{\pm}=\xi^{\pm\alpha}=\exp(\pm i\kappa x\cos\theta) \tag{25}$$

valid, so that $p_0=\exp i\kappa(\pm x\cos\theta+y\sin\theta)$. These two solutions ierefore reduce approximately to the known solution for deep-water aves in this region.

For the shallow-water region, $x$ is small, and $\xi\sim 1$, so that the series in 24 converge very slowly. There are other solutions, however, that onverge more rapidly. One of these is

$$q_1=\xi^{\alpha}F(\alpha+\beta+\tfrac{1}{2},\ \alpha-\beta+\tfrac{1}{2},\ 1,\ 1-\xi). \tag{26}$$

n general, there is a second solution, obtainable from $q_1$ by changing the gn of $\alpha$. However, because the third argument of $F$ in eq 25 is an teger, this solution becomes identical with $q_1$ and it is necessary to find more complicated expression, which involves a logarithmic singularity $\xi=1$. This is $q_0$, where

$$\pi q_0=\{\psi(l)+\psi(m)+\log[\gamma^2(\xi-1)]\}q_1+F_1(l,m,1,1-\xi)$$
$$+F_1(m,l,1,1-\xi)+2F_3(l,m,1,1-\xi), \tag{27}$$

nd

$$l=\alpha+\beta+\frac{1}{2};\quad m=\alpha-\beta+\frac{1}{2};\quad \psi(l)=\frac{d}{dl}\log\Gamma(l);\quad \gamma=1.7811\ldots;$$

$$F_1(l,m,n,x)=\frac{\partial}{\partial l}F(l,m,n,x);\quad F_3(l,m,n,x)=\frac{\partial}{\partial n}F(l,m,n,x).$$

The expressions for $q_0$ and $q_1$ are too elaborate to be readily calculated umerically. However, just as it was possible to obtain approximations $q_{\pm}$ for small values of $\xi$, so it is possible to obtain approximations to and $q_1$, that are valid when $1-\xi$ is small, and both $|\alpha|$ and $\beta$ are large. This latter condition is fulfilled when the slope of the bottom is small d the waves are incident from a direction that is not too nearly parallel the beach.)

The approximation is

$$\left.\begin{aligned} q_0&=N_0[2(\kappa x/s)^{\frac{1}{2}}],\\ q_1&=J_0[2(\kappa x/s)^{\frac{1}{2}}],\end{aligned}\right\} \tag{28}$$

ere $N_0$ and $J_0$ are the Neumann and Bessel functions, respectively.

This is again very satisfactory, for these are the solutions obtained
Stoker and others from the shallow-water theory [2].

The eq 25 thus gives simple expressions for $q_+$ and $q_-$ in deep water, eq 28, simple expressions for $q_0$ and $q_1$ in shallow water. It remain find the relations between the four solutions. These are the kn formulas for the analytic extensions of the hypergeometric function may be written

$$\left.\begin{aligned} q_1 &= A(-\alpha,\beta)q_+ + A(\alpha,\beta)q_-, \\ q_0+iq_1 &= B(\alpha,\beta)A(-\alpha,\beta)q_+, \end{aligned}\right\}$$

where

$$\left.\begin{aligned} A(\alpha,\beta) &= \Gamma(2\alpha)/\Gamma\left(\alpha+\beta+\frac{1}{2}\right)\Gamma\left(\alpha-\beta+\frac{1}{2}\right), \\ B(\alpha,\beta) &= \sin(2\pi\alpha)/\cos[\pi(\alpha+\beta)]\cos[\pi(\alpha-\beta)]. \end{aligned}\right\}$$

The function $A(\alpha,\beta)$ can be transformed, by using known prope [6, p. 1] of the gamma function, into

$$A(\alpha,\beta) = [-2\pi\alpha|B(\alpha,\beta)|]^{-\frac{1}{2}}\exp[i\Theta(\alpha,\beta)],$$

where the function $\Theta(\alpha,\beta) = -\Theta(-\alpha,\beta)$ is difficult to evaluate. Physic this function represents the total change in phase of the waves as t move from deep to shallow water, and is of little interest. Of gre interest is the change in amplitude of the waves, and this is independ of the function $\Theta$.

Using the known asymptotic expansions of the Bessel functions

$$\left.\begin{aligned} N_0(\sigma) &= \sin(\sigma-\pi/4)/(\pi\sigma/2)^{\frac{1}{2}}, \\ J_0(\sigma) &= \cos(\sigma-\pi/4)/(\pi\sigma/2)^{\frac{1}{2}}, \end{aligned}\right\}$$

it is seen that for the shallow-water region,

$$q_0+iq_1 = \pi^{-\frac{1}{2}}(s/\kappa x)^{\frac{1}{4}}\exp i\left[\frac{3\pi}{4} - 2\left(\frac{\kappa x}{s}\right)^{\frac{1}{2}}\right].$$

For the deep water region,

$$q_+ = \exp(-i\kappa x\cos\theta).$$

Hence, the second of eq 30 shows that a wave of unit height in deep w will have the height

$$H = [2\alpha/|B(\alpha,\beta)|]^{\frac{1}{2}}(s/\kappa x)^{\frac{1}{4}}$$

in shallow water. For small values of $s$, this simplifies further, to

$$H = (\tfrac{1}{2}\cos\theta)^{\frac{1}{2}}/(\kappa h)^{\frac{1}{4}}.$$

The dependence of $H$ on the water depth is well known from the shallow-water theory [1, Chap. VII, p. 291] and the factor $(\cos\theta)$ easily be derived from considerations of the laws of refraction and assumption that the energy is propagated in the direction of the The factor $(\frac{1}{2})^{\frac{1}{2}}$ results from the fact that, in deep water, the group vel is half the phase velocity, whereas in shallow water the two are equ

## 5. Summary

An approximate wave equation has been derived, for the propagation gravity waves on water of any depth.

Although the precise conditions for the validity of the approximations ave not been established, they appear to be justifiable in a wide variety cases.

A byproduct of this investigation is an approximate solution of the sual equation connecting the deep-water wave number, $\kappa$, to the wave mber $k$ at depth $h$. The supposedly exact equation is eq 15, and its proximate solution is given by eq 13, in a closed form suitable for use analytic applications.

Certain applications of the results here obtained will be reported sewhere.

## 6. References

H. Lamb, Hydrodynamics. Sixth edition, Cambridge University Press, 1932.

J. H. Stoker, Surface waves in water of variable depth. Quarterly of Applied Mathematics, vol. 5, pp. 1–54, 1947.

F. Klein, Die hypergeometrische Reihe. Leipzig, 1894.

A. R. Forsyth, Treatise on differential equations. Sixth edition, MacMillan, 1948.

T. M. MacRobert, Spherical harmonics. Dover Publications, New York, 1947.

W. Magnus and F. Oberhettinger, Formulas and theorems for the special functions of mathematical physics. Chelsea, New York, 1949.

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# *PAPER CHROMATOGRAPHIC PATTERNS OF GENETICALLY DIFFERENT TISSUES: A CONTRIBUTION TO THE BIOCHEMICAL STUDY OF INDIVIDUALITY**

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The discovery of differences related to descent, and the description in chemical terms of how a known genotypic condition present in the zygote may determine, or be related to, a definite morphology of the adult organism, are two of the aims of genetics. Paper partition chromatography of fresh tissues or body fluids in animal and plants provides a simple tool for the pursuit of these aims. In this report data will be presented showing how this technique, an outgrowth of the work initiated by Hadorn and Mitchell,[1] makes it possible to recognize genotypic differences hidden under identical morphological features; indications will be given, too, as to the range of applicability of the procedure used. Much remains to be studied yet, especially at the biochemical level, on the very material here presented. It seems worth while, however, at the present stage of these investigations, to summarize some of the results obtained. It is hoped that this might stimulate similar work on the same or other organisms and especially attract the interest and the cooperation of the biochemists.

*Chromatographic Technique.*—Both general procedures of chromatographic separation, by descending flow and by capillary ascent of the solvent, have been used in most cases. As the former allows a better separation of the spots than the latter, if not otherwise stated all the data and photographs reported have been obtained from chromatograms developed by descending flow, following standard techniques (see, e.g., Balston and Talbot[2]). For ascending chromatograms the technique of Williams and Kirby,[3] as modified by Hadorn and Mitchell,[1] has been used.

Sheets of Whatman No. 1 filter paper of various sizes were prepared as follows. In case of the descending chromatograms a light pencil line was drawn 3 in. from the edge to be dipped into the solvent, and samples for chromatography were placed at 1 in. or 4-cm. intervals along this line. In case of the ascending chromatograms the pencil line was drawn 1.5 cm. from the edge and samples applied at 1-cm. intervals. Details about the treatment of animal and plant tissues and fluids will be given below.

Several solvents as described by Kirby Berry, *et al.*,[4] have been tried; most of the descending chromatograms, however, have been obtained using either of the following mixtures.

(A) 2 parts (by volume) of *n*-propanol and 1 part of 1% ammonia.

(B) 4 parts of *n*-butanol, 5 parts of distilled water, 1 part of glacial acetic acid are poured into a separating funnel in the given order, and thoroughly shaken for about three minutes; separation of the two phases is allowed for at least two hours, at room temperature. Sheets for chromatography are hung in the tank, letting the vapours of the lower phase impregnate the paper for about one hour; the upper phase is then poured into the troughs.

Mixture (A) does not need to be renewed at each run, but (B) must be freshly prepared for each determination. For ascending chromatograms mixture (A) has been used. Solvent A will be indicated as 2P:1A; solvent B as B:A.

For descending determinations Chromatocabs Model 300 of University Apparatus Co., Berkeley, California, and for ascending runs glass jars of various sizes have been used. Time of development (or length of runs) has varied between 2 and 24 hours at 22°–25°C. Most of the reported determinations were obtained from 22-hr. runs; in this time the front of the solvent covers almost to the edge the length of Whatman No. 1 sheets. At the end of the period the sheets were removed from the tanks or jars and allowed to dry in the air at room temperature. Known mixtures of amino-acids have been constantly developed for control, together with the materials to be analyzed. Two groups of separating substances have been studied: fluorescent materials as revealed by use of a G.E. ultra-violet lamp (Black-Light Lamps B-H 4); ninhydrin-positive materials as revealed by spraying the developed chromatograms with a 0.2% solution of ninhydrin in 95% ethanol, to which 5% of 2,4,6-collidine was added before use. While the fluorescing substances may last unaltered for several weeks or months, the ninhydrin-positive materials fade out quickly, in a few days. Recording of the data and photographs of the chromatograms were correspondingly taken about 24 hr. after the ninhydrin spraying. Since no attempt was made toward a qualitative or quantitative identification of the chemical nature of the separating spots, the best type of record proved to be the direct photography of the fluorescent or ninhydrin-positive patterns. Black-and-white as well as colored photographs were taken and kept as permanent records. Cross checking of the constancy of the results were made by comparing (*a*) one-dimensional chromatograms obtained from the same genetic material at different times, (*b*) one-dimensional chromatograms developed for different times with the same solvent, (*c*) two-dimensional chromatograms with the one-dimensional ones obtained with the same solvents. Every statement concerning the presented material is based on the analysis of a minimum of three repetitions, carried out independently in different days, on at least three individuals of each genotype; in each experiment a minimum of ten samples per genotype were developed.

## DROSOPHILA MELANOGASTER

*Culture Conditions.*—The medium for growing flies had the following composition: molasses, 237 ml.; corn meal, 473 g.; brewer's dry yeast, 40 g.; agar, 30 g.; water, 2840 ml. After cooking and bottling the medium was seeded with Fleischmann's bakers' yeast or with a pure strain of *Saccharomyces cerevisiae.* In order to avoid crowding and to insure thereby constancy in the flies size, batches of about 100 eggs were collected and transferred to half pint bottles. Development took place at 25 ± 1°C. Flies which had undergone development on medium occasionally infected by green molds were not discarded but analyzed separately in order to check the influence of different diets. The observation made by Hadorn and Mitchell[1] that substances from the food contained in the gut of either larvae or flies are not present in sufficient quantities to interfere with any of the determinations were confirmed in the course of these experiments.

*Preparation of the Flies.*—Observations to be reported in this paper relate only to the chromatographic patterns of adult flies of various ages. Only morphological mutants not affecting eye pigment production were studied and, in order to get rid as much as possible of the pigment component in the chromatograms, flies have always been decapitated after etherization. These were then quickly washed in 95% ethanol and boiled for one minute in distilled water. After removing adhering water by placing them on filter paper, flies were transferred directly to the chromatograph sheets and squashed thoroughly onto the paper using a flat glass pestle. The spots so produced were allowed to dry in air at room temperature. Either single flies or three flies were mashed to form a single spot. Residual tissues were not removed. Once dry the sheets are storable for months and chromatograms can be developed at any convenient time; precautions against bacterial or mold contamination must be observed, of course.

*Basic Pattern of the Adults and Its Constancy.*—Comparison of the ninhydrin-positive patterns obtained from various Drosophila strains did not show any appreciable difference. The rest of this report concerning such material will be limited therefore to fluorescing substances. There is very little correspondence between the ninhydrin-positive and the fluorescing patterns. $R_f$ values are given without standard errors since these would give the impression of a higher accuracy than one can actually obtain in such measurements; spots being often quite large, the actual measurement of the distance covered with respect to the front of the solvent is necessarily somewhat arbitrary. The given values, however, are the mean of at least 60 independent readings, and were mostly taken from 12 hr.

as well as from 20 hr. descending runs. As it will be shown, there is good agreement between values here reported and the ones published by Hadorn and Mitchell.[1]

By basic pattern it is meant the maximum number of distinguishable spots for any particular material and solvent. As will be shown below, variations in the patterns can always be related to this "basic pattern" in that the position and color of each spot does not change in different strains of this species. Differences between strains can refer to number and/or intensity, and/or size of the spots of the fluorescing materials. The particular combination of spots of any one strain gives a very characteristic pattern.

TABLE 1

$R_f$ VALUES OF FLUORESCING SPOTS IN THE BASIC PATTERN OF DECAPITATED *Drosophila melanogaster*. SOLVENT: 2P:1A

| FEMALES | | | MALES | | |
|---|---|---|---|---|---|
| SPOT NO. | COLOR | $R_f$ | SPOT NO. | COLOR | $R_f$ |
| 1 | Yellow | 0.088 | 1 | Yellow | 0.088 |
| 2 | Blue | 0.174 | 2 | Blue | 0.179 |
| 3 | Green | 0.215 | 3 | Green | 0.208 |
| 4 | Greenish-blue | 0.230 | 4 | Greenish-blue | 0.259 |
| 5 | Bluish | 0.342 | 5 | Blue | 0.346 |
| 6 | Yellow | 0.393 | 6 | Blue | 0.397 |
| 7 | Bluish | 0.462 | 7 | Yellow | 0.432 |
| 8 | Blue | 0.513 | 8 | Blue | 0.495 |
| | | | 9 | Yellow | 0.569 |

TABLE 2

$R_f$ VALUES OF FLUORESCING SPOTS IN THE BASIC PATTERN OF DECAPITATED *Drosophila melanogaster*. SOLVENT: B:A

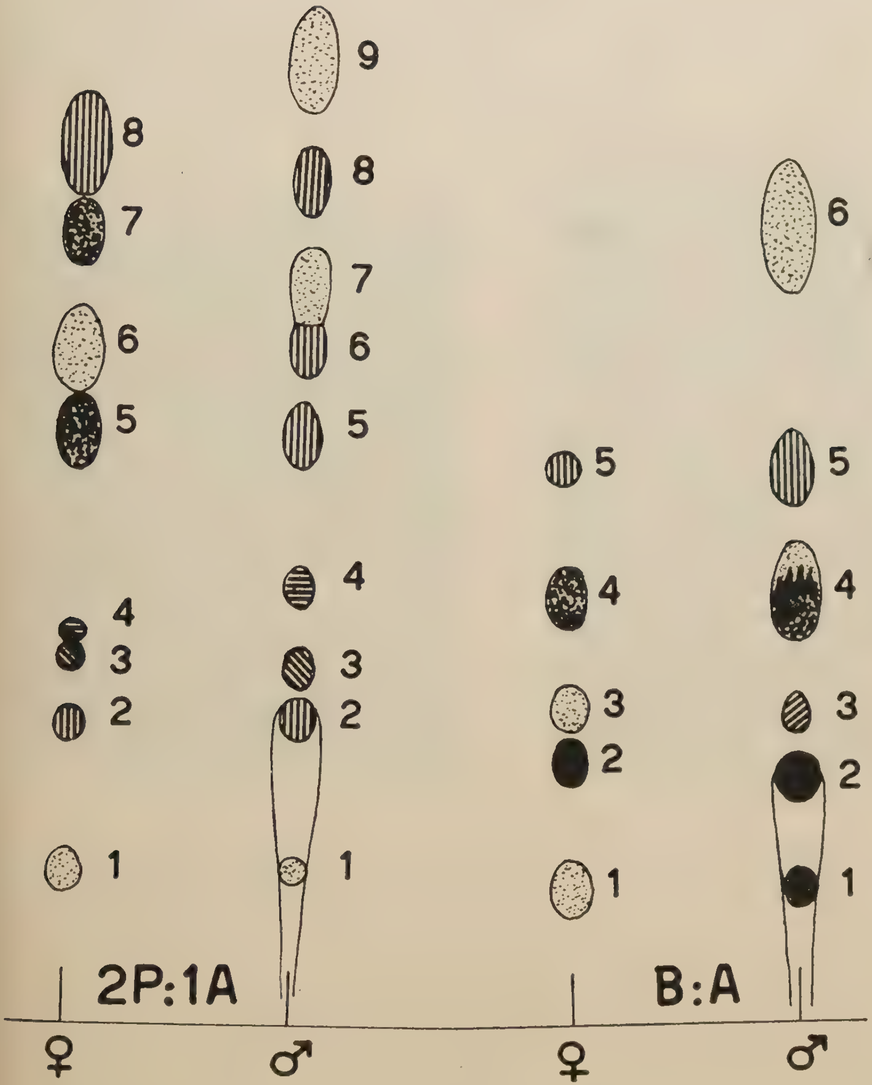
| FEMALES | | | MALES | | |
|---|---|---|---|---|---|
| SPOT NO. | COLOR | $R_f$ | SPOT NO. | COLOR | $R_f$ |
| 1 | Yellow | 0.081 | 1 | Bluish | 0.078 |
| 2 | Purplish-blue | 0.157 | 2 | Purplish-blue | 0.145 |
| 3 | Yellow | 0.186 | 3 | Greenish-orange | 0.182 |
| 4 | Bluish-yellow | 0.254 | 4 | Bluish-yellow | 0.254 |
| 5 | Blue | 0.328 | 5 | Blue | 0.328 |
| | | | 6 | Yellow | 0.470 |

Females: 2P:1A: In the basic pattern of fluorescing materials separating from decapitated females one can distinguish eight spots. For description of the colors and $R_f$ values see figure 1, and table 1.

B:A: In the basic pattern of decapitated females one can distinguish five spots. For description see figure 1 and table 2.

Males: 2P:1A: In the basic pattern of fluorescing materials separating from decapitated males one can distinguish nine spots. For description see figure 1 and table 1.

B:A In the basic pattern of decapitated males one can distinguish six spots. For description see figure 1 and table 2.


9
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2P:1A
6
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4
3
2
1
5
4
3
2
1
B:A
♀
♂
♀
♂

FIGURE 1

Schematic representation of the basic patterns of decapitated *Drosophila melanogaster*.

With both solvents spot No. 2 in males makes a very bright blue stripe almost from the bottom of the chromatogram, which makes the difference with respect to females very obvious, and which often masks completely spot No. 1. This very striking difference between the fluorescing patterns of females and males is related to the presence of the blue fluorescing substance, which, according to Hadorn and Mitchell,[1] is especially concentrated in the testes, Malpighian tubes and haemolymph.

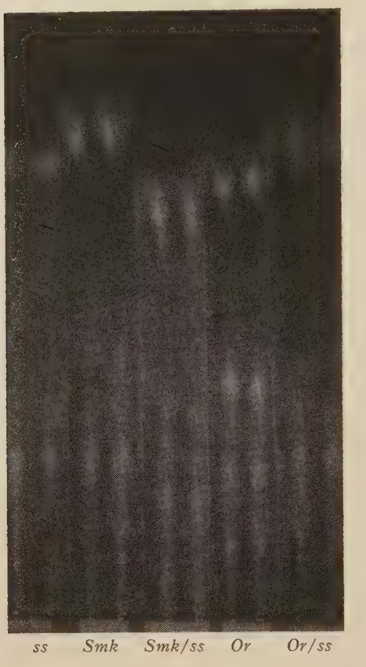

FIGURE 2

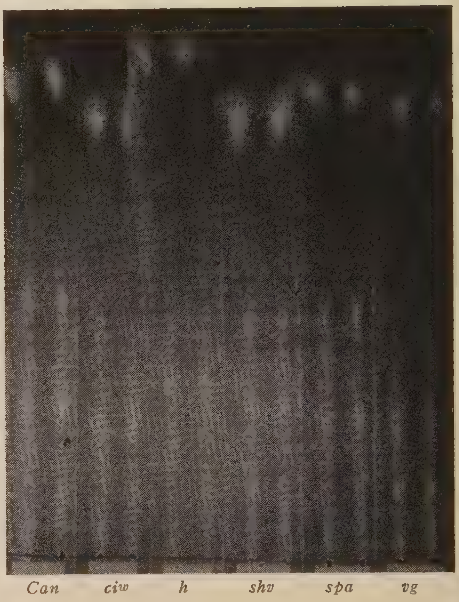

FIGURE 3

Fig. 2. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* females. Solvent: 2P:1A. Genotypes: *ss/ss;* homozygous wild type Samarkand; Samarkand/*ss;* homozygous wild type Oregon-R; Or/*ss*. Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

Fig. 3. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* females. Solvent: 2P:1A. Genotypes: wild type Canton homozygous; $ci^w/ci^w$; *h/h; shv/shv; spa/spa; ss/ss; vg/vg.* Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

The constancy of the observed patterns was studied with respect to two variable factors: feeding and age. As previously stated, different diets do not seem to influence appreciably the fluorescing patterns. In order to check the influence of age, samples of 200 eggs were collected for four strains (Canton, Samarkand, *shv*, *ss*) at five days intervals for a period of a month. Embryonic and larval development as well as metamorphosis and hatching took place at 25°C.; at the twelfth day after egg collection, when all adults had hatched, flies were transferred to room temperature for aging. Correspondingly six groups of adults of the following ages from hatching were mashed onto the paper: ♀♀ 6–7 days; 10–11 days; 15–16 days; 21–22 days; 26–27 days; 31–32 days; ♂♂ 8–9 days; 12–13 days; 17–18 days; 23–24 days; 28–29 days; 33–34 days. A minimum of twelve chromatograms per age group and per strain was observed. While in the case of males age of the adults does not seem to influence at all the fluorescing pattern, every spot being quite constant over a period of about one month, in the case of females some effects of age were observed. Spot No. 2 (with both solvents) is very bright in early age but fades out and disappears almost completely after the twelfth day of adult life; spots No. 6 and 8 (2P:1A) are weaker in early age but reach the maximum of intensity and remain constant after the tenth day of life. As a consequence of these results, all the data reported below refer to animals aged at least for two weeks; in this way the age variable could be eliminated. In most cases two chromatographic patterns for each genotype are presented in the photographs in order to give an idea of the constancy of results.

*Patterns of Wild Type Strains.*—Four wild type strains were studied: Canton, Samarkand, Oregon-R, Florida 2436. A comparison of the photographs of three of these strains (see Figs. 2 and 6) will give an idea of the type of differences to be observed between strains. Oregon-R, e.g., has in females spots No. 3 and 8 much brighter than the other two; on the other hand Samarkand has the bluish No. 4 much more evident than either Canton or Oregon. The direct comparison of the chromatograms where the differences in color and shade of the fluorescing patterns can be appreciated or of their colored photographs allows a much easier distinction of the patterns of various genotypes. No attempt was made to evaluate quantitatively the differences in intensity and size of the spots. Among the strains available there was one which had been derived from the Oregon-R strain and had been inbred by brother-sister mating for 68 generations at the time when the material was used for chromatography. The pattern of fluorescing materials obtained from flies of this inbred strain was very similar to that of the Oregon strain. A comparison of a series of several dozens of chromatographic patterns obtained from single individuals of Oregon-R and of Oregon-R-inbred revealed that in the latter the individual variability was much smaller than in the former and that, correspondingly, the inbred strain had much more sharply clear-cut spots than the mass cultured strain from which it had been originally derived. It became possible, therefore, to evaluate the degree of genetic homogeneity by simple inspection of a series of individual chromatograms.

*Patterns of Mutant Strains.*—The different mutant strains tested are the following: *Bx*, *bt*, *c*, $ci^W$, *en*, $ev^2$, *h*, $L^4$, $Ly/D^3$, *shv*, *spa*, *ss*, $ss^a$, *vg*, *wv*. For description of these mutants see Bridges and Brehme,[5] and D.I.S. 21.[6] Only those genotypes have been selected that do not affect appreciably the color of eyes or bodies. Mutants having different eye or body colors had previously been analyzed by Hadorn and Mitchell;[1] besides, it was thought of some interest to concentrate on mutants whose end-product, as observed at the phenotypic level, was not of an obvious chemical nature, such as pigment production, but rather affected a morphological structure, such as wing or bristle shape and size. Each of the tested strains proved to give a distinctive fluorescing pattern. Some of the differences are quite clear cut, e.g., one or more spots are entirely lacking, while some of the other differences are not so obvious, especially when considered in a black and white photograph. Figures 3 and 4 give, however, a picture of the type

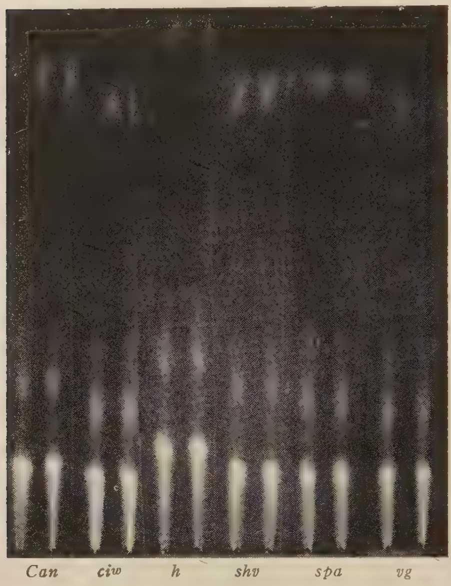

FIGURE 4

*P*₁
*f*
*gt*
*P*₁
*f*
*gt*

FIGURE 5

Fig. 4. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* males. Solvent: 2P:1A. The same genotypes as in Fig. 3. Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

Fig. 5. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* females and males. Solvent: 2P:1A. Genotypes (from left to right): 2 chromatograms of homozygous wild type Oregon-R-S, ♀; 2 chromatograms of *f/f*, ♀; 2 chromatograms of *gt/gt*, ♀; 2 chromatograms of homozygous wild type Oregon-R-S, ♂; 1 chromatogram of *f*, ♂; 2 chromatograms of *gt/gt*, ♂. Each chromatogram from three decapitated flies. Length of run: 20 hours.

of differences observed. As it will be noticed, a remarkable parallelism of results is to be seen when comparing the patterns of females and males of the same strain. A similar conclusion can be drawn with respect to the comparison of patterns derived from the same genotype but with different solvents. A detailed description of each pattern could be given in terms of number, intensity and size of the spots. This seems superfluous, however, at the present stage. What should be stressed again is the extraordinary constancy of results which makes it possible to maintain that each genotype has a characteristic biochemical pattern as revealed by this procedure.

*Can*
*ss*
*Can/ss*
*ss/Can*

FIGURE 6

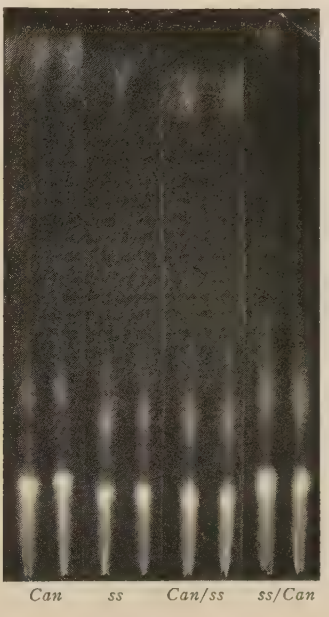

FIGURE 7

Fig. 6. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* females. Solvent: 2P:1A. Genotypes: homozygous wild type Canton; *ss/ss;* $F_1$ from ♀ Canton × ♂ *ss;* $F_1$ from ♀ *ss* × ♂ Canton. Two chromatograms for each genotype shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

Fig. 7. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* males. Solvent: 2P:1A. Genotypes: the same as Fig. 6, but in the male sex. Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

*Patterns of Single Gene Differences.*—The results so far presented indicate that each of the tested genotypes imparts a remarkable specificity to the body constituents of the flies which can be separated by paper chromatography. It was not known, however, whether such differences could be related to the particular gene mutations marking the used strains or whether they were due to the action of the specific allele involved plus that of the remaining genetic background or the background alone. Since the mutant strains had been kept in the laboratory for many years, and, besides, some of them had been originally found in unrelated strains, it could well be that the amount of genetic difference between the mutant strains was really much greater than the one revealed by the presence of a morphological mutant. To get some evidence on this point it has been possible to take advantage of some special strains kindly provided by Dr. Jack Schultz. These were (see D.I.S. 25[7]): p 1 (brother-sister inbred since 1947 from Oregon-R-S); p 4 (*f* Oregon-R-S, derived from crosses in 1947 to inbred stock from Oregon-R-S, inbred since then); p 7 (*gt* Oregon-R, similar origin).

As it can be seen in the accompanying photographs (Fig. 5) clear-cut differences are to be seen between the said strains. Since here one is probably dealing with a common genetic background in all the strains and with single gene differences, it seems safe to conclude that the biochemical specificity as revealed by this procedure falls under the control of single genetic loci.

*Patterns of Recessive Gene Heterozygotes.*—To this stage the analysis had been carried either on strains morphologically identical but differing in their geographic origin or on mutants easily distinguishable at the morphological level. The fact that genotypic differences could be revealed by paper chromatography irrespective of whether they would or would not appear in the phenotype, led to testing whether one could distinguish by this method two individuals phenotypically similar, but one being homozygous for the dominant allele and the other heterozygous for a recessive mutant at the same locus. With this idea in mind, the chromatograms of several recessive gene heterozygotes were studied and compared with the patterns of the homozygous parental strains. The same recessive mutant was crossed to more than one wild type strain. The following wild type and mutant strains were used for this experiment: Canton, Samarkand, Oregon, *bt*, $ci^W$, $ey^2$, *shv*, *spa*, *ss*, $ss^a$, *vg*. In every tested case it has been possible to show that the heterozygous individuals give a chromatographic pattern which differs from the one of its wild type homozygous parent as well as from that of the homozygous recessive. Figures 6, 7, 8, bring evidence to this point and show that this is true irrespective of the wild type strain used (e.g., *ss* was crossed with the three strains mentioned above). By this technique it became possible, therefore, to uncover genotypic differences otherwise hidden by dominance.

*Maternal Effects.*—While analyzing patterns of heterozygous individuals it became evident that in some cases some constant difference was to be found between heterozygotes for the same gene derived from reciprocal crosses. This was the case for the following combinations: +/*shv* - *shv*/+; +/*vg* - *vg*/+; +/*ss* - *ss*/+, using as wild type strain anyone of the three above mentioned; in the case of *hairy* the two reciprocal hydrids could be distinguished only when using Samarkand as parental wild type strain. In such combinations, while the heterozygous individuals could always be distinguished from the homozygous dominant, the fluorescing pattern was more similar to that of the female parent than to that of the male. Figures 6, 7, 9, 10 show how such material effect can appear in the chromatograms. All the mentioned cases have been crosschecked using the two solvents and studying both sexes. No such maternal effect was found in the heterozygotes for the following mutants: *bt*, $ci^W$, *en*, *spa*, $ss^a$.

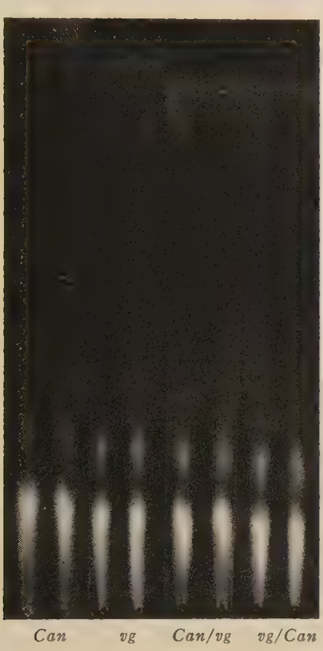

FIGURE 8

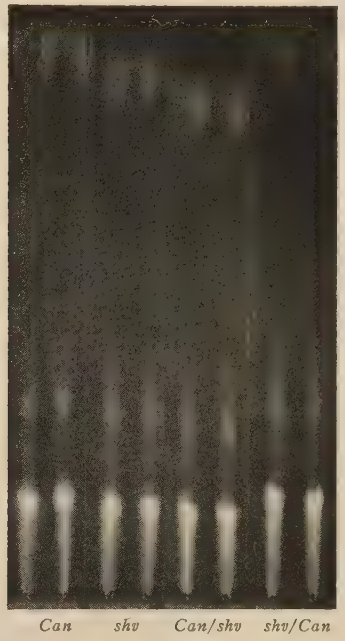

FIGURE 9

Fig. 8. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* males. Solvent: B:A. Genotypes: homozygous wild type Canton; *vg/vg;* $F_1$ from ♀ Canton × ♂ *vg;* $F_1$ from *vg* × ♂ Canton. Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

Fig. 9. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* males. Solvent: 2P:1A. Genotypes: homozygous wild type Canton; *shv/shv;* $F_1$ from ♀ Canton × ♂ *shv;* $F_1$ from ♀ *shv* × ♂ Canton. Two chromatograms for each genotype are shown. Each chromatogram from three decapitated flies. Length of run: 20 hours.

## Plant Materials

In order to ascertain the range of applicability in other organisms of this technique for studying the biochemical specificity imparted by the genotype, similar investigations were carried on other animals and plants kindly made available to the writer. Some results obtained with plants will follow, as these give indications of a genotypic control of the biochemical specificity of various tissues of the same organism.

Three tissues have been used: anthers, root tips, and leaves. Anthers were directly mashed onto the paper without any pretreatment using a flat glass pestle. One or more anthers were used so as to form a spot about $^3/_8$ in. in diameter; residual hard tissue was not removed. Root tips were thoroughly washed with tap water in order to remove completely any soil, inorganic and organic materials; they were then dried with filter paper, and cut to 1 cm. long pieces. From 4 to 8 such pieces, according to their thickness and juiciness, were directly mashed onto the paper with a glass pestle to form a spot of the mentioned size; hard parts were not removed. Leaves were thoroughly ground with a pestle in a mortar; with the aid of a capillary tube about 10 lambdas of the obtained juice were allowed to be absorbed by the paper. When leaves were too dry to allow this procedure some of the ground material was brought onto the paper with the aid of tweezers and enough of the oozing juice was allowed to get absorbed by the paper to form a spot about $^3/_8$ in. in diameter. The leaf debris was then removed. After the various mashed tissues and juice had been allowed to dry at room temperature, descending chromatograms were developed for 20 hr. at 25°C. using the said solvents. Most satisfactory separation was obtained from B:A.

*Or*
*ss*
*Or/ss*
*ss/Or*

FIGURE 10

Fig. 10. Chromatographic patterns of fluorescing materials in *Drosophila melanogaster* females. Solvent: B:A. Genotypes: homozygous wild type Oregon-R; *ss/ss;* $F_1$ from ♀ Oregon-R × ♂ *ss;* $F_1$ from ♀ *ss* × ♂ Oregon-R. Two chromatograms for each genotype are shown. Each chromatogram from the decapitated females. Length of run: 20 hours.

*Tomato (Solanum lycopersicum L.).*—Chromatograms of anthers, leaves and root tips of a wild type strain, of the *male sterile*$_2$ mutant as described by Rick,[8] and of the heterozygote obtained by crossing the two homozygous strains were obtained. This recessive mutant was found in the Pearson variety of tomato. Its description is: "Smears of mature anthers reveal no pollen, either normal or aborted. Sections show concave anther walls and a small amount of degenerated material present in the locule. Meiosis proceeds normally. Microspores degenerate shortly after formation of the tetrads." The fluorescing, as well as the ninhydrin-positive patterns obtained from each of the three tissues were characteristic for each genotype, and the heterozygote could be easily identified in each case. Such identification was especially clear in the case of the root tips. Here the recessive mutant had two very clear fluorescing spots ($R_f$ about 0.7 and 0.8) not present at all in the wild type strain; the heterozygous pattern, similar in every other respect to that of the dominant genotype, showed the presence of the two extra fluorescing spots present in the mutant. The ninhydrin positive material allowed, too, an easy recogni-

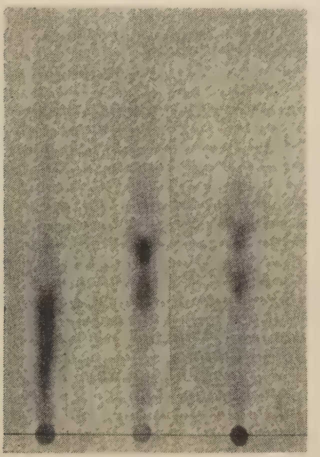

FIGURE 11

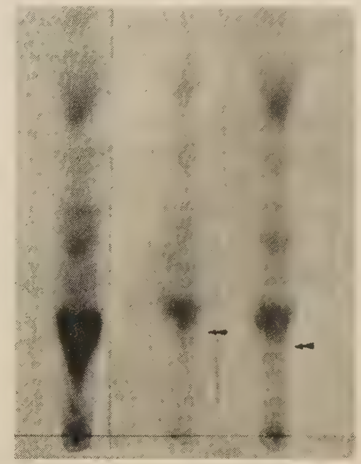

FIGURE 12

Fig. 11. Chromatographic patterns of ninhydrin-positive materials in muskmelon leaves. Solvent: B:A. Genotypes: homozygous wild type; *yg/yg;* heterozygous +/*yg*. Each chromatogram from a drop of leaf juice. Length of run: 20 hours.

Fig. 12. Chromatographic patterns of ninhydrin-positive materials in muskmelon root tips. Solvent: B:A. Genotypes: same as in Fig. 11. Each chromatogram from smeared root tips. Length of run: 20 hours. Arrows indicate whitish halo corresponding to very bright blue colored fluorescing substance present in *yg/yg* and the heterozygote.

tion of the heterozygotes, as this gave a pattern intermediate between the ones of the parental strains.

*Muskmelon* (*Cucumis melo L.*).—In this material three strains have been studied: a wild type, a *yellow-green* mutant as described by Whitaker,[9] and the heterozygote for this recessive condition. The total chlorophyll content of normal green plants is slightly over twice that of the *yg* mutant. The ratio of chlorophyll *a* to chlorophyll *b* in normal green plants is 2.42, and in the yellow-green mutant 3.18. In the heterozygous condition, yellow green is completely recessive, in that there is no significant departure in the relationship of total chlorophyll content in the normal green plants and in the heterozygotes for the *yg* mutant. Chromatograms were obtained from leaves and root tips. Using both tissues distinctive patterns for fluorescing and ninhydrin-positive materials were obtained for the two parental strains; this made the recognition of the heterozygote possible. As can be seen in figures 11 and 12, while the heterozygous leaf gives a chromatogram practically indistinguishable from that of the homozygous recessive, in the case of the root tip chromatogram an intermediate pattern is observed. This is true for the fluorescing material also; the light-colored halo indicated with an arrow on figure 12 corresponds to a very bright bluish fluorescing area, which can be seen as very intense in the *yg* mutant, less intense but quite evident in the heterozygote, but completely absent in the normal strain.

## Discussion

Data here presented indicate that (1) the biochemical constitution of an organism or of its parts as revealed by the paper chromatographic technique is exceedingly constant and is largely independent of dietary and environmental conditions; (2) characteristic differences at the biochemical level can be found when different genotypes are compared; (3) the method is sensitive enough as to uncover genotypic differences masked by dominance phenomena; (4) single gene as well as multifactorial differences can influence in a definite way the biochemical makeup of an organism; (5) various tissues of an organism, give, as expected, different biochemical patterns; but when the patterns of the same tissue coming from organisms genetically different are compared, constant biochemical differences can be found irrespective of whether the morphology of the studied tissue is directly affected by the genotype involved; (6) maternal influence at the biochemical level and not affecting the morphological features can be uncovered with this technique.

No serious attempt has been made to recognize the chemical nature of the substances separating in the chromatograms, and this shall be the necessary prerequisite for more detailed work in the field. The only indirect piece of evidence on this problem is this: hydrolyzed Drosophila and plant tissues have been analyzed with the same chromatographic technique, and after hydrolysis no difference was to be found, whether in the fluorescing or the ninhydrin-positive patterns, when comparing various genotypes. It is not known whether this is due to a masking effect of the great amount of aminoacids and other substances released by the hydrolysis and separating in the chromatograms. It appears, however, that part at least of this effect is due to the control imparted by the genotype to the building up of larger molecular structures, starting from simpler chemical substances common to every genotype. On this view the chromatography of untreated tissues would separate part at least of such large molecular structures and would thereby give a clue to and understanding of the biochemical specificity imparted by the genotype.

The idea that the genotype controls the specificity of proteins or of other large molecular structures is as old as the earliest speculations on the physiology of gene action. Some indirect evidence on this point has been brought by immunological studies and by grafting of tissues. Inbred strains or identical twins give identical reactions while this is not the case for sibs (see L. Loeb[10]). Taking advantage of the great sensitivity of the paper chromatographic technique, it seems feasible to carry this analysis a few steps further and perhaps to describe in known chemical terms products of a certain genetic condition. We do not know whether the substances isolated by this technique are to be considered excretion products, or cellular saps, metabolites or catabolites, or what definite constituent of the analyzed tissues. The remarkable constancy of results, on the one hand, and the fact that the tissue seems to fall under the biochemical control of the genotype, on the other hand, point to the particular significance of the described patterns. Results obtained in other organisms, such as fish, comparing the chromatographic patterns of a definite tissue (e.g. muscle) of different species (Buzzati-Traverso and Rechnitzer[11]), indicate, too, that the degree of biochemical similarity is somehow related to the degree of taxonomic relationship. This being the case, the precise chemical analysis of the observed differences could elucidate several obscure points concerning the physiology of gene action and phylogenetic affinities in chemical terms. Without indulging too much in speculations, however, it seems safe to maintain that this simple technique provides us with a very useful tool for genetic studies. The possibility of revealing genetic differences up to now not evident in the phenotype looks like the most promising result, with respect to theoretical as well as to practical applications. A series of other genetic problems, such as the comparison between mutants and their phenocopies, or the tracing back in the course of development of the biochemical differences evident in the adult stage, is now open to analysis from this angle.

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† Visiting Professor from the Institute of Genetics, University of Pavia, Pavia, Italy. This work was supported by funds from the University of California and from the Rockefeller Foundation.

[1] Hadorn, E., and Mitchell, H. K., PROC. NATL. ACAD. SCI., **37,** 650 (1951).

[2] Balston, J. N., and Talbot, B. E., *A Guide to Filter Paper and Cellulose Powder Chromatography,* H. Reeve Angel and Co., Ltd., London, 1952, p. 145.

[3] Williams, R. J., and Kirby, H., *Science,* **107,** 481 (1948).

[4] Kirby Berry, H., Sutton, H. E., Cain, L., and Berry, J. S., *Univ. Texas Publ. No.* 5109, 22 (1951).

[5] Bridges, C. B., and Brehme, K. S., *Publ. No. 552, Carnegie Instn.* (*1944*).

[6] Drosophila Information Service 21, 69 (1947).

[7] Drosophila Information Service 25, 47 (1951).

[8] Rick, C. M., *Genetics,* **30,** 347 (1945).

[9] Whitaker, T. W., *Plant Physiol.,* **27,** 263 (1952).

[10] Loeb, L., *The Biological Basis of Individuality,* Charles C Thomas, Springfield, Ill., and Baltimore, 1945.

[11] Buzzati-Traverso, A. A., and Rechnitzer, A. B.; *Science,* 117, 58 (1953).

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# Pigments from a Marine "Red Water" Population of the Dinoflagellate *Prorocentrum micans*

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## THEORETICAL PART

Appropriate chemical and physical factors in aquatic environments are conducive to the reproduction of numerous species of phytoplankton (singled-celled algae) in enormous numbers. The resulting localized populations of these microscopic plant cells and their relatively rich carotenoid stores result in the occasional appearance of striking yellowish, orange, red, or ruddy colors in near-shore ocean waters or in lakes, rain-ponds, or even in snow [Smith (12); Lwoff and Lwoff (8); Galtsoff (3); Fox (1)]. Only through microscopic examination is it possible to determine the causative species in cases of so-called "red tide," or, more suitably speaking, "red water." Galtsoff (3) has listed numerous species of microplanktonic organisms which may be responsible for the occurrence of marine "red water." Fox and Sargent (2) demonstrated the rich stores of $\beta$-carotene in the algal flagellate *Dunaliella salina* as the seat of red color in natural or industrial brine ponds. In some instances, disturbances in the water, e.g., the breaking of waves on or near the shore, may, during a bloom of "red water," be accompanied by striking momentary flashes of nocturnal bluish luminescence emitted by the whole wave front.

During July, 1952, an occurrence of red water took place along the Pacific Coast, extending from the Northwest gradually down into the waters off southern California, thus providing an opportunity for an examination of pigment extracts.

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[1] Contribution No. 1758.

[2] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 623.

The following three groups of compounds were given special attention: chlorophylls, carotenoid pigments, and colorless, fluorescing compounds including a search for the polyene, phytofluene, encountered in a great number of carotenoid-producing land plants (14). This latter part of the investigation gave a negative result and is not reported in detail. Although colorless, fluorescent substances appeared in each chromatogram (just above the carotene fraction), no phytofluene or similar polyenes could be observed. The fluorescence was rather bluish when compared with the more greenish shade of phytofluene fluorescence; neither did sharp maxima appear in the extinction curves whereas phytofluene shows in hexane very sharp maxima at 348 m$\mu$ and 367 m$\mu$.

### *Starting Material*

As a part of a broad oceanographic project of the Scripps Institution of Oceanography, samples of red water were collected at depths of from 0 to 7 m. at each of several stations. Aliquots were saved for various analytical processes, and twin aliquots were preserved for determination of the kinds of microplankton present and the relative numbers of these. Populations varied widely both vertically and horizontally in different places of collection. The chief sample from which the plankton was recovered for this pigment analysis was taken from the sea surface July 11, 1952, 12:00 M, at a station 32° 48.8′ N; 117° 19.1′ W (off the Scripps Institution).

Microscopic examination revealed: (*a*) *Prorocentrum micans* (a brownish ovoid dinoflagellate of major and minor axes 60 $\mu$ by 15 $\mu$, respectively), *ca.* $4.5 \times 10^6$ cells/l.; (*b*) two other dinoflagellate species, *Ceratium furca* and *Ceratium tripos* (?): *ca.* $3 \times 10^4$ cells/l.; (*c*) diatoms: *ca.* $6 \times 10^3$ cells/l.; (*d*) zooplankton: *ca.* $6 \times 10^3$ cells/l. *Prorocentrum* thus represented nearly 99% of the species enumerated, and, although relative masses were not actually estimated, it seems probable that this alga was similarly preponderant in that respect as well. If, considering each cell as a prolate spheroid, we use the estimated figure of $5.8 \times 10^{-8}$ g. per living *Prorocentrum* cell, the 87 g. used in our first analysis amounted to some $10^9$ cells, weighing about 8.7 g. on a dry basis.

For the extraction with methanol and a first resolution on a sugar column we followed, in general, the excellent directions given by Strain, Manning, and Hardin (13) who have investigated the pigments of several diatoms, brown algae, dinoflagellates, and sea anemones. We found that, after this preliminary resolution, *Prorocentrum* extract require a further resolution on calcium carbonate columns (see below).

### *Chlorophyll*

Crude extracts of our material showed a greenish color; however, chromatographic analysis of the preserved material did not reveal the presence of any significant amounts of chlorophyll, with the possible exception of traces of chlorophyll c. The greenish-gray section of the sugar column was found to contain pheophytin a (Fig. 1) and a few minor, similar zones, probably also pheophytin a′. Although the organisms were collected in the living state and treated with methanol without delay, the possibility had to be considered that chlorophyll a might have suffered from acidic or enzymatic degradation. When the fresh material was treated with, and preserved in, methanol containing 1% dimethylaniline, and worked up within 24 hr., the same chromatogram as mentioned was obtained. However, when the fresh centrifuged cells from a laboratory culture of the same species were killed by a 30-sec. immersion of the containing tube into near-boiling water, intact chlorophyll a could be identified as the predominant green pigment. This conclusion was drawn from a comparison of the light-extinction curve of the extracted green pigments with known data on chlorophyll a (obtained from other sources) and on pheophytin **a**.

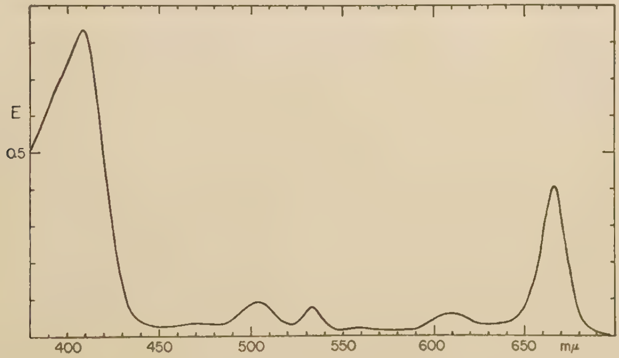

Fig. 1. Spectral curve (in ether) of pheophytin a *ex Prorocentrum micans.*

It should also be mentioned that the spectral curve determined for the total pigment extracts of the freshly killed *Prorocentrum* cells are quite like those reported for other similarly colored algae (e.g., diatoms and brown algae) such as the brown alga *Coilodesme* studied by Haxo and Blinks (4). In such forms under natural conditions the existence of chlorophyll is well established.

### *Peridinin*

As seen from the Experimental Part the main carotenoid pigment in our *Prorocentrum* extracts was identified as peridinin. This pigment had been observed in extracts of the dinoflagellate *Peridinium cinctum* by earlier authors such as Schütt (10) and Seybold *et al.* (11). Peridinin was obtained by Strain, Manning, and Hardin (13) who observed that it forms the main chromatographic zone of *Peridinium cinctum* extracts. According to these authors it is, among other features, characterized by its hypophasic behavior when partitioned between hexane and aqueous methanol as dilute as 65%. Peridinin is almost certainly identical with sulcatoxanthin (probably $C_{40}H_{52}O_8$) isolated in microcrystalline form by Heilbron, Jackson, and Jones (5) from *Anemonia sulcata.*

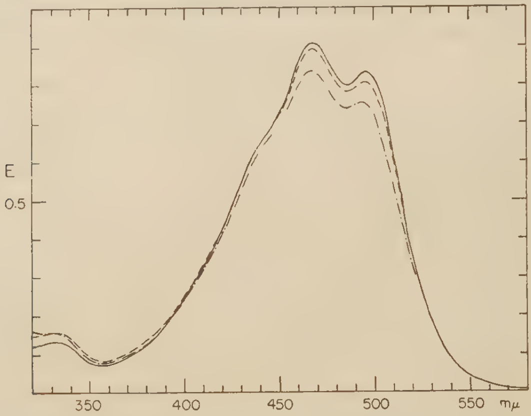

FIG. 2. Spectral curve (in benzene) of peridinin *ex Prorocentrum micans:* full line, fresh solution; dashed line, after refluxing for 30 min.; and dash-dot line, after iodine catalysis and illumination with a daylight lamp for 15 min.

Strain, Manning, and Hardin (13) gave a spectral curve for this pigment referring to the region, 400–500 mμ in petroleum ether and showing two typical maxima, viz. at 455 and 485 mμ. Figure 2 represents a more extended curve. Since the total of our best microcrystalline sample amounted to only 2 mg., this curve is presented in only a qualitative form.

The stereoisomerization of dissolved peridinin at higher temperatures was described by Strain *et al.* (13) as follows: "This resulted in the separation of a pale, diffuse red-orange band containing neoperidinin above the band containing unchanged peridinin. Faint traces of other red–orange bands were adsorbed above the neoperidinin and very small quantities of still another pigment were adsorbed below the peridinin."

We have carried out with peridinin some *trans* → *cis* isomerization experiments by means of refluxing, iodine catalysis in light, and exposure to intense sunshine. Subsequent chromatograms on calcium carbonate showed three new zones, termed neo $A$, $B$, and $C$ (from top to bottom).[3] The separation of $B$ and the minor isomer $C$ was difficult, while $A$ separated from $B + C$ very easily. Each of these *cis* forms, when submitted to similar treatment and chromatographed on calcium carbonate, produced again the same members of the stereoisomeric peridinin set. The all-*trans* form thus obtained did not separate from naturally occurring peridinin in the mixed chromatogram test.

The spectrophotometrically determined composition of the stereoisomeric peridinin quasi-equilibrium was, after iodine catalysis, all-*trans*: neo $A$: neo $B + C = 59{:}29{:}12$. The composition of insolated solutions was similar, while even 2 hr. refluxing yielded less *cis* form than the other treatments mentioned. After standing 24 hr. at room temperature the composition of a benzene solution was, all-*trans*: neo $A$ : neo $B + C = 74{:}18{:}8$. The increased adsorption affinity of *cis* forms as compared with that of the all-*trans* compound is similar to that observed in the stereoisomeric capsanthin set, another representative of the hydroxylated carotenoid ketones to which class peridinin probably belongs [cf. Strain *et al.* (13)].

### *Other Carotenoids*

Besides peridinin, the algal pigment contained a large number of xanthophylls, about 18 zones being observed on the column, although a few of them represented neo-isomers formed during laboratory operations. Most of these pigments had absorption spectra similar to that of β-carotene. They all were epiphasic when tested with hexane and 65% methanol but hypophasic in the presence of 90% methanol. Ether solutions of most of them gave a slow color reaction with conc. hydrochloric acid while the epiphase also remained colored. Sizable amounts of fucoxanthin or similar pigments were absent as well as carotenoids containing longer chromophoric chains. Only a minute fraction of the polyene pigments represented hydrocarbons, mainly β-carotene. This preponderance of xanthophylls is generally true of the photosynthetic cells of marine plants (9), but exceptions have been observed, e.g., in the brine flagellate *Dunaliella salina* (2).

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[3] Extinction maxima in benzene (Beckman): $A$, 463, 490 mμ; $B$, 468, 494 mμ; and $C$, 468, 493 mμ; upon iodine catalysis, the maxima 467 and 493 mμ were observed in all three instances.

Summarizing, it can be concluded that the approximate composition of *Prorocentrum micans* pigment corresponds to the values listed in Table I.

TABLE I

*Approximate Composition of the* Prorocentrum micans *Pigment*

| "Red water" pigment (mg./100 g. wet material; water content *ca.* 90%) | |
|---|---|
| Chlorophyll (mainly chlorophyll a, estimated as pheophytin a) | 17 |
| Peridinin (+ neoperidinins) | 10 |
| Other hypophasic carotenoids | 8 |
| Epiphasic carotenoids (mainly β-carotene) | 1 |

## EXPERIMENTAL

### *Collection of the Material*

Collections were made from waters at La Jolla and a few miles off shore therefrom, from one of the University of California research vessels. The method adopted was to halt the vessel in areas wherein the reddish color of the water and the red–orange surface scums were richest. Embarking from the ship in a rowboat (to avoid possible contamination by oil or bilge from the vessel), the collector skimmed the surface water into the rounded mouth of a conical net, with a 20-cm. opening, and made of No. 20 silk bolting cloth, equipped at the cod-end with a small (130 ml.) wide-mouthed bottle. Although the algal cells are smaller than the individual pores of such a net, the pores soon became clogged sufficiently to permit great numbers of the plankton to be collected in the bottle, while the water passed out through the net openings. These relatively concentrated collections were pooled in large, wide-mouthed jars from which much water could be decanted a few hours later, and the residual "mud" of plankton was finally concentrated in centrifuge tubes; after decantation of the water, the sediment was washed out with methanol as a preservative and thus transferred into glass-stoppered bottles, and then kept in a refrigerator until transferred to the laboratory for analysis.

### *Extraction and Resolution of the Pigment*

Eighty-seven grams of freshly collected wet material was suspended for transportation in about 125 ml. of methanol, and was kept at 4°C. until extracted as follows. It was centrifuged and the supernatant decanted to be eventually combined with the total extract. The latter was prepared by shaking mechanically the solid residue five times with 200 ml. abs. methanol each and then twice with 150 ml. of benzene each.

After every shaking, the material was centrifuged and the liquid decanted. Each extraction required ¼ hr. (The solid residue, when ultimately ground up with sand in a mortar, no longer yielded any colored extract.) All combined benzene–methanol extracts were separated into two layers by adding an almost saturated sodium chloride solution in a separatory funnel. The lower phase was re-extracted twice with benzene which was then added to the main benzene layer. This dark-green benzene solution was washed methanol-free in a continuous washing apparatus (7), dried with anhydrous sodium sulfate, filtered, and evaporated to dryness *in vacuo* at room temperature while a slow stream of nitrogen bubbled through the capillary. In order to remove the benzene completely, a small volume of hexane was then added, and the evaporation was repeated. The oily residue was taken up in 100 ml. of hexane and filtered, and this stock solution was stored in the cold room.

(*a*) The chromatographic resolution will first be described for a 1:10 aliquot of the total extract corresponding to 8.71 g. of the starting material. The solution was poured onto a 24 × 4.8 cm. column of Powdered Confectioner's Sugar ("C and H"), and developed with hexane. In the following chromatogram the figures at left designate thickness of zones, in millimeters:

10 pale greenish-yellow, yellowish-pink fluorescent in ultraviolet light: fraction *A*
7 colorless interzone
3 dark gray (traces)
15 pale orange: neoperidinins fraction *B*
11 dark orange: peridinin
4 yellow
3 red–orange
3 pale yellow
5 dark yellow fraction *C*
3 red–orange
7 colorless interzone
24 yellow
73 grayish-green, intense red fluorescent in ultraviolet light: pheophytins
40 pale greenish, same fluorescence: pheophytins: fraction *D*
20 colorless, nonfluorescent interzone
Filtrate: yellowish (carotenes), dark-blue fluorescence in ultraviolet light: fraction *E*

The fractions *A–D* were separated by cutting the extruded column and eluting the respective portions with 95% ethanol on fritted-glass Büchner funnels. Fractions *B* and *C* were transferred into benzene by the addition of water, then washed, dried, and filtered. Fractions *A* and each of the two components of *D* were evaporated, and the residue was taken up in ether.

*Fraction A*. Spectral maximum (Beckman) at 450 mμ in ether (minor maximum at 630 mμ).

*Fraction B*. This fraction was chromatographed on a calcium carbonate column which, when developed with benzene + 2% acetone, gave a main red zone (all-*trans*-peridinin about 0.6 mg.) and above it, well separated by an interzone, three neoperidinins (total, about 0.3 mg.) which were fractionated, after having combined similar material originating from larger experiments (see below).

*Fraction C*. This fraction proved to be a complicated mixture of pigments and hence its correct resolution required a larger scale experiment (see below).

*Fraction D*. The pheophytins were transferred into ether in which the spectral curves were taken. Both showed maxima of pheophytin a.

*Fraction E* (chromatographic filtrate). This hexane solution was concentrated to a small volume and rechromatographed on calcium carbonate (developer, hexane). The carotenes were thus washed into the filtrate while the diffuse bluish fluorescent column was eluted with ethanol; the eluate was transferred into hexane and evaporated to dryness. The oily, fluorescent residue did not give any characteristic spectral maxima. The carotenes were rechromatographed on calcium hydroxide + Celite 3:1 (developer, hexane). Three zones were obtained, viz., neo-β-carotene U, all-*trans*-β-carotene, and neo-β-carotene B, the total amount being 0.1 mg.

(*b*) A large-scale experiment was carried out with an aliquot of $\frac{9}{10}$ of the original extract for which purpose chromatography on three 30 × 8 cm. sugar columns was required, each of which gave a picture similar to that described under (*a*). In these experiments, instead of dividing the column by cutting, the main components were fractionally washed down into the chromatographic filtrate, as follows. First, the column was washed with pure hexane until the carotenes and the blue-fluorescent substance reached the suction flask, whereupon the receiver was changed and the development continued with hexane containing 0.25% *n*-propanol until the pheophytins were washed down. The components of the zones below peridinin (corresponding to fraction *C*) were obtained by means of hexane + 1% propanol; and finally, when the propanol content of the developer had been increased to 2%, the peridinins (fraction *B*) were clearly separated from some top zones and were cut out from the extruded column.

*Fraction B.* The peridinins were eluted with alcohol, transferred into benzene, evaporated *in vacuo* to dryness (7 mg. microcrystalline crude product). This was dissolved in benzene and rechromatographed on a 24 × 4.8 cm. calcium carbonate column (developer, benzene + 2% acetone). The main bottom zone was cut out, eluted as above, transferred into benzene, washed, dried and evaporated to complete dryness. This sample was dissolved in a minimum amount of benzene and crystallized by adding hexane dropwise and cooling. A scarlet precipitate of microcrystals appeared. The preparation was recrystallized in a similar manner from ether–hexane and weighed then about 2 mg. This sample was used for spectral estimations and for some isomerization experiments. For the latter purpose, however, more peridinin was used, after chromatographic purification, originating from mother liquor materials.

In the Loewe-Schumm Grating Spectroscope (Zeiss), the visually established maxima for peridinin are: in hexane, 490, 457 mμ; in benzene, 502, 465 mμ; and in carbon disulfide, 518, 482, (449) mμ. Heilbron *et al.* observed 516, 482, (450) mμ for "sulcatoxanthin" ($CS_2$).

*Fraction C.* This faction was first developed on sugar with hexane + 0.5% propanol, yielding four main zones, each of which was rechromatographed on calcium carbonate (developer, benzene + 1–3% acetone). Finally, in all, 18 zones were observed, a few of which evidently represented *cis* isomers, and some others represented only traces. An examination of 13 zones in the Loewe-Schumm Visual Grating Spectroscope (Zeiss) showed maxima in benzene located as follows (chromatographic sequence on calcium carbonate; parentheses designate indistinct bands):

| | mμ | mμ |
|---|---|---|
| (Top) | 487 | 460 |
| | 463 | — |
| | 464 | 435 |
| | 470 | 440 |
| | 495 | 462 |
| | 491 | 459 |
| | 491 | 460 |
| | 470 | (440) |
| | 470 | (440) |
| | 494 | 461 |
| | 496 | 464 |
| | 496 | 460 |
| (Bottom) | 497 | 463 |

### *Detection of Intact Chlorophyll a in Cultured* Prorocentrum micans

This laboratory culture grown in enriched sea-water was kindly supplied to us by Dr. Beatrice Merwin. The cells were collected by low-speed centrifugation (total volume of the packed cells, about 0.05 ml.). A microscopic examination indicated healthy cells mixed with some debris, probably consisting of precipitated iron. The fresh cells were killed by dipping the centrifuge tube in near-boiling water for ½ min. whereby their color changed from brown to olive green. They were extracted twice with 5 ml. of abs. methanol. The first extract was deep greenish yellow. (The second extract was very light greenish yellow; a subsequent acetone extract was practically colorless.) The pigment of the first extract (maxima in methanol at 664, 440 m$\mu$) was transferred into light petroleum ether, and the xanthophyll content of the solution was removed by shaking with 90% methanol. The then green epiphase was washed methanol-free, dried with sodium sulfate, adsorbed at the top of a small "powdered sugar" column, and developed with petroleum ether containing 2% acetone. The chromatogram contained a clear bluish green main zone with slight traces of a greyish zone below, the latter being suggestive of pheophytin. The green pigment was washed down into the filtrate with petroleum ether + 4% acetone; when concentrated, this solution was bluish green in color. Its spectral curve showed maxima at 665 and 432 m$\mu$ (in methanol), typical for chlorophyll a [cf., e.g., Ref. (9)].

## SUMMARY

Extracts of a practically pure sample of the dinoflagellate *Prorocentrum micans* occurring in "red water" along the coast of southern California were subjected to chromatographic analysis. The main carotenoid was identified as peridinin; minor carotenoids belonged chiefly to the xanthophyll type, but carotenes were found in small quantities. Phytofluene or a similar fluorescent colorless polyene was absent, although other fluorescent compounds were encountered. Preserved extracts yielded pheophytin a in place of the corresponding chlorophyll; however, in freshly heat-killed cells the presence of chlorophyll a was demonstrated.

## REFERENCES

1. Fox, D. L., Animal Biochromes. Cambridge Univ. Press, London, 1953.
2. Fox, D. L., and Sargent, M. C., *Chemistry & Industry* **57**, 1111 (1938).
3. Galtsoff, P., *Sci. Monthly* **68**, 108–17 (1949).

4. Haxo, F. T., and Blinks, L. R., *J. Gen. Physiol.* **33,** 389 (1950).
5. Heilbron, I. M., Jackson, H., and Jones, R. N., *Biochem. J.* (London) **29,** 1384 (1935).
6. Kylin, H., *Hoppe-Seyler's Z. physiol. Chem.* **166,** 39 (1927).
7. LeRosen, A. L., *Ind. Eng. Chem., Anal. Ed.* **14,** 165 (1942).
8. Lwoff, M., and Lwoff, A., *Compt. rend. soc. biol.* **105,** 454 (1930).
9. Rabinowitch, E. I., Photosynthesis and Related Processes, Vol. *I*, p. 644. Interscience Publ., New York, 1945.
10. Schütt, *Ber. deutsch. botan. Ges.* **8,** 9 (1890).
11. Seybold, A., Egle, K., and Hülsbruch, W., *Botan. Arch.* **42,** 239 (1941).
12. Smith, G. M., Fresh Water Algae of the United States. McGraw-Hill, New York, 1933.
13. Strain, H. H., Manning, W. M., and Hardin, G., *Biol. Bull.* **86,** 169 (1944).
14. Zechmeister, L., and Sandoval, A., *Arch. Biochem.* **8,** 425 (1945).

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FOX, DENIS L. Animal biochromes and structural colours. Cambridge University Press, 379 pp., 1953. (Unavailable for exchange.)

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# The Scattering of Sound from the Sea Surface

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It is assumed that the equation of the sea surface is $z=\zeta(xyt)$, and that the time average $\Phi=\langle\zeta(x'y't)\zeta(x''y''t)\rangle$ is a function only of $\xi=x''-x'$, $\eta=y''-y'$. The scattering coefficient of long-wave sound is calculated and shown to be

$$\sigma=(c^2k^2/4\pi)^2\int\int\Phi(\xi\eta)\exp[-ik(a\xi+b\eta)]d\xi d\eta,$$

where $2\pi/k$ is the wavelength of the sound, and $a$, $b$, $c$ are, respectively, the sum of the $x$, $y$, $z$ direction cosines of the incident and scattered rays. For short-wave sound, the formula is more complicated, but independent of the wavelength of the sound, as it should be. However, it is shown that experiments with short waves yield much less information about the sea surface than do those with long waves. This is unfortunate, since the latter experiments are much more difficult than the former.

## INTRODUCTION

scattering of underwater sound by the sea face was studied, under the designation "sur-beration," during the war.[1] It has also been t the study of scattered sound or other radia-furnish information concerning the geometry natics of the sea surface.[2,3] In order that such on may be obtained from the experimental neoretical analysis of the problem is needed. ysis is difficult, and many approximations are to reach simple formulas. Despite this, it is t the Eqs. (21) and (36) below will be useful rpose indicated.

### The Sound Field

oustic pressure will be the sum of the incident $_0$ and secondary $p_1$ which is in turn the sum ected and scattered sound. The incident sound ven, to a sufficient approximation, by

$$p_0(xyz)=P[\exp(ikr_0)]/r_0 \qquad (1)$$

s the distance from the center of the source to xyz and $P$ depends only on the direction of $r_0$. that all integrals in the following equations it is necessary to assume that the source is ctional and illuminates only a finite area of vise infinite sea surface; $P$ is therefore not

ondary (reflected plus scattered) sound will then be a solution of the wave equation and will consist only of outgoing waves. Helmholtz's theorem[4] is therefore applicable in the form

$$4\pi p_1(A)=\int\int_S\left\{\frac{\partial p_1}{\partial\nu}[\exp(ikr_1)/r_1]-p_1\frac{\partial}{\partial\nu}[\exp(ikr_1)/r_1]\right\}dS, \qquad (2)$$

where

$S$ is the sea surface, $z=\zeta(x,y,t)$;
$\nu$ is the normal to $S$, positive toward the source of sound;
$A$ is any point on the same side of $S$ as the source of sound; and
$r_1$ is the distance from $dS$ to $A$.

This formula expresses the value of $p_1$ at a general point in terms of its boundary values and those of its normal derivative on the sea surface.

If the source of sound is underwater, the surface $S$ is a "pressure release," and, to a very good approximation, one may set

$$p_0+p_1=0 \quad \text{on } S, \qquad (3)$$

which determines the boundary values of the secondary radiation in terms of those of the (known) incident radiation. It is not so easy to obtain a good approximation for the normal derivative; one may, however, note that if $S$ were a plane rather than an irregular surface, one would find

$$\partial p_0/\partial\nu=\partial p_1/\partial\nu \quad \text{on } S. \qquad (4)$$

If $S$ is not so irregular that some parts of it are shadowed by others, one may assume that Eq. (4) still holds; however, in deep shadows it would be more reasonable to suppose that $(\partial p_0/\partial\nu)+(\partial p_1/\partial\nu)=0$, so that some caution must be exercised in applying results obtained from Eq. (4). With this warning, it will be assumed that both

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of Sound in the Sea," NDRC Summary Technical vision 6, Vol. 8, Part II, chap. 12. "Principles of Sound," NDRC Summary Technical Reports, Divi- 7, chap. 5. The reports have been reprinted and by the National Research Council.
ıleikin, *Fisika Moria* (Physics of the Sea) (Izdatelstvo auk., Moscow, 1941), 833 pp.
nd W. H. Munk, *The Measurement of the Roughness rface from Photographs of the Sun's Glitter*. Part I. The niversity of California, Scripps Institution of Ocean-ference No. 52–61, 1952). Contains bibliography.

[4] B. B. Baker and E. T. Copson, *The Mathematical Theory of Huyghens Principle* (Oxford University Press, London, 1939), pp. 23–28.

Eqs. (3) and (4) are valid, so that Eq. (2) may be written

$$4\pi p_1(A)=\int\int_S (\partial/\partial\nu)\{[p_0 \exp(ikr_1)]/r_1\}dS. \quad (5)$$

If the source of sound is in the air, the sea surface is "hard" to a very good approximation, and the boundary condition $(\partial p_0/\partial\nu)+(\partial p_1/\partial\nu)=0$ replaces Eq. (3). The boundary values of $p_1$ are now difficult to determine with the same precision as $(\partial p_1/\partial\nu)$, but the approximation $p_0=p_1$ on $S$ is valid to the same extent as Eq. (4). This results in an equation identical with Eq. (5) except for a negative sign on the right side.

If the source of sound is underwater, and $p_1$ is due to a hard, rough sea floor, this same equation applies. Clearly, intermediate cases are conceivable, but will not be considered here. Except for the sign, which is usually immaterial, Eq. (5) thus applies to all three cases. If $r_0$ and $r_1$ are everywhere much greater than the wavelength, this may be further simplified to

$$4\pi p_1(A)=\int\int (P/r_0r_1)(\partial/\partial\nu)\{\exp[ik(r_0+r_1)]\}dS.$$

If the source is sufficiently directional, the denominator $r_0r_1$ may be replaced by its value at the origin of coordinates $r_{00}r_{10}$, while in the exponential

$$r_1+r_0=r_{10}+r_{00}+(ax+by+cz)$$

is used. The quantities $a$, $b$, $c$ are, respectively, the sums of the $x$, $y$, $z$ direction cosines of $r_{10}$ and $r_{00}$. The replacement of $z$ by $\zeta$ in the exponential, $\partial/\partial\nu$ by $\partial/\partial z$ and $dS$ by $dxdy$ finally reduces this to

$$4\pi p_1(A)=\pm\{ikc[\exp(ikr_{10})]/r_{10}\}$$

$$\times\int\int \bar{p} \exp[ik(ax+by+c\zeta)]dxdy, \quad (6)$$

where

$$\bar{p}=P[\exp(ikr_{00})]/r_{00}.$$

For future reference, it is to be noted that if $\zeta$ is identically zero, $p_1$ will consist entirely of the specularly reflected radiation. Hence, to the present approximation,

$$-4\pi p_0(A')=\{ikc[\exp(ikr_{10})]/r_{10}\}$$

$$\times\int\int \bar{p} \exp[ik(ax+by)]dxdy, \quad (7)$$

where $A'$ is the image of $A$ in the $xy$ plane. The notation

$$p_r(A)=\mp p_0(A')$$

will be used.

Thus far, it has been tacitly assumed that the function $\zeta$ is independent of the time $t$. Presumably, if the sea surface does not change too much during the time $2\pi/k$ so that $\zeta$ is a slowly varying function of $t$, the Eq. (6) will remain valid to the degree of approxin achieved.

### STATISTICAL THEORY FOR LONG-WAVE F

The Eq. (6) can be further simplified if length, $2\pi/k$ is much greater than the large $|\zeta|$. Then

$$\exp(ikc\zeta)=1+ikc\zeta \text{ approx.}$$

The first term results in specularly reflected the scattered radiation is given by

$$p_s(A)=p_1(A)-p_r(A)$$

$$=\mp\{k^2c^2 \exp(ikr_{10})/4\pi r_{10}\}$$

$$\times\int\int \bar{p}\zeta \exp[ik(ax+by)$$

The intensity of the scattered sound, per unit will be

$$I_s=|p_s|^2r_{10}^2.$$

Because the sea surface is not constant, $I$ with time; only its mean value $\langle I_s\rangle$ will be here. This is

$$\langle I_s\rangle=(k^2c^2/4\pi)^2\int\int\int\int \bar{p}(x'y')\bar{p}^*(x''y'')$$

$$\times\langle\zeta(x'y't)\zeta(x''y''t)\rangle$$

$$\cdot\exp\{ik[a(x'-x'')+b(y'-y'')]\}$$

$$\times dx'dy'dx'$$

since only $\zeta$ depends on $t$. The function

$$\Phi=\langle\zeta(x'y't)\zeta(x''y''t)\rangle$$

therefore contains all the information abc surface that is required to determine $\langle I_s\rangle$ quantities in the integral depend only on t radiation. Being a time average, $\Phi$ does not c but may depend on the four coordinates points $x'$, $y'$ and $x''$, $y''$. However, if the se homogeneous, $\zeta$ will depend only on the two $\xi=x''-x'$, $\eta=y''-y'$; throughout the follov be supposed that this is the case. Using $\xi$, $\eta$ of variables, and introducing the abbreviati

$$J(\xi\eta)=\int\int \bar{p}(x'y')\bar{p}^*(x'+\xi, y'+\eta)dx$$

Eq. (11) simplifies to

$$\langle I_s\rangle=(k^2c^2/4\pi)^2\int\int J(\xi\eta)\Phi(\xi\eta)$$

$$\times\exp[-ik(a\xi+b\eta)]$$

uate this integral, one needs to know more function $\Phi(\xi, \eta)$; from Eq. (12), it readily at

$$\Phi(\xi, \eta)=\Phi(-\xi, -\eta), \qquad (15)$$

$$-\Phi(00)\leqslant\Phi(\xi\eta)\leqslant\Phi(00)=h^2, \qquad (16)$$

the rms value of $\zeta$, the displacement of the sea om the plane $z=0$. (It is no loss of generality to at the arithmetic mean, $\langle\zeta\rangle$, is zero.) Any operties of $\Phi$ must be found by observation, y be assumed that $\Phi(\xi, \eta)\rightarrow 0$ when $(\xi^2+\eta^2)^{\frac{1}{2}}$ much larger than the length of the average urface waves. The function $J(\xi, \eta)$ will also zero for large $\xi$ and $\eta$, but only when $(\xi^2+\eta^2)^{\frac{1}{2}}$ reater than the dimensions of the area of the t is insonified by the beam of incident radia- is dimension is much greater than the length ins of surface waves, one may approximate y replacing $J(\xi, \eta)$ with

$$J(0, 0)=\int\int|\bar{p}|^2dxdy; \qquad (17)$$

$$\langle I_s\rangle=J(0, 0)\sigma, \qquad (18)$$

$$/(4\pi)^2\int\int\Phi(\xi\eta)\exp[-ik(a\xi+b\eta)]d\xi d\eta \qquad (19)$$

nsionless quantity that may be called the coefficient, or more descriptively, the scat- ss section for unit solid angle per unit area of e.

cing the function

$$)=\int\int\Phi(\xi\eta)\exp[-i(k_x\xi+k_y\eta)]d\xi d\eta, \qquad (20)$$

implifies to

$$\sigma=(k^2c^2/4\pi)^2S(ka, kb). \qquad (21)$$

ion defined by Eq. (20) may be called the ctrum of the surface waves; it depends on the nents, $k_x$ and $k_y$, of the wave number vector, epends on both the direction and wavelength soidal components of the surface waves.

refore possible, by measuring $\sigma$ for long wave to obtain values of the spacial spectrum. tely, it is necessary to vary the directional s $a$ and $b$ as well as the frequency of the inci- tion. This may be difficult in practice. The urements that are easily made are for scat- k to the source (reverberation), and these are ade only at very small glancing angles. The tal difficulty of measuring $S$ in this way is great.

t deserves further notice. If $k$ is so small that um function $S$ can be replaced by $S(0, 0)$ in Eq. (21), the scattering coefficient is proportional to $k^4$, or inversely proportional to the fourth power of the wavelength of the radiation. This is the analog of the Rayleigh law for visible light scattered by a molecular medium.

### STATISTICAL THEORY FOR SHORT-WAVE RADIATION

The difficulties in arranging the geometry of source and receiver are relatively small in one case. If, instead of sound, light is used, the sun[3] can be employed as source, and as the receiver, a camera in an airplane. In this way, the angular parameters are readily varied within wide limits. In this section, the formulas of the preceding section will be employed to calculate $\sigma$ for very short-wave sound, no attempt being made to introduce the modifications required by the electromagnetic theory of light.

The simplifications of the preceding section are then no longer possible, and the full statistical theory of the sea surface must be invoked. Let $W(z)$ be the distribution function of $\zeta$, defined by

$$\langle F[\zeta(xyt)]\rangle=\int F(z)W(z)dz, \qquad (22)$$

which is to hold for every function $F$ such that the time average of $F(\zeta)$ exists. In general, $W$ will also depend on $x$, $y$, but if the surface is statistically homogeneous, $W$ will depend only on $z$. An important special case of Eq. (22), for this as well as other applications, is

$$\langle\exp[-ik\zeta(xyt)]\rangle=\int\exp(-ikz)W(z)dz=Q(k); \qquad (23)$$

$Q$ is known as the characteristic function associated to $W$ and $\zeta$.

On taking the time average of both sides of Eq. (6), the simple result

$$4\pi\langle p_1(A)\rangle=\mp 4\pi p_0(A')Q(kc) \qquad (24)$$

is readily obtained. It is reasonable[5] to identify $\langle p_1\rangle$ with $p_r(A)$, the coherently reflected radiation. Then $Q(kc)$ is recognized as the (amplitude) reflection coefficient of the surface. Since $p_0(A')$ is very small except when the angles of incidence and reflection are equal, say to $\theta$, the amplitude reflection coefficient is very approximately

$$R=\mp Q(2k\cos\theta). \qquad (25)$$

It is readily seen from Eqs. (12) and (23) that $|R|\rightarrow 1$ for very long-wave radiation ($k\rightarrow 0$), and $R\rightarrow 0$ for very short-wave radiation ($k\rightarrow\infty$).

An important special case is the Gaussian distribution, for which

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[5] This, and other considerations that follow, are entirely analogous to the refraction and scattering of light by three-dimensional molecular media; see, M. Born *Optik* (Berlin, 1933), Sections 74, 75, and 81.

$$W=[1/(2\pi)^{\frac{1}{2}}h]\exp(-z^2/2h^2),\quad Q=\exp(-k^2h^2/2),$$

$h$ being the rms value of $z$. Then

$$R=\exp(-2k^2h^2\cos^2\theta),\tag{26}$$

and it is possible to estimate the reflection coefficient in special cases. Thus, if the frequency of the sound is 25 kc, $k=1$ cm$^{-1}$; if the sea is quite smooth, one may take $h=100$ cm, so that it is seen that $|R|$ will be very small unless $\cos\theta\leqslant 0.01$.

When $\cos\theta=0.01$, $|R|=0.135$, so that even at such small glancing angles and for such smooth seas, the loss on reflection will be more than 15 db. Possibly this description is unusual: in ordinary terminology, it indicates that the image of the source will be very distorted, and probably broken up into many images or parts of images. This is the idea on which the discussions of Shuleikin and Munk and Cox are based.

The energy that is thus lost from the coherently reflected beam will be found in the incoherently scattered radiation, $p_s=p_1-p_r$. Again defining $I_s$ by Eq. (10), Eq. (6) yields

$$\begin{aligned}\langle I_s\rangle+|p_r|^2r_{10}^2&\\ =(kc/4\pi)^2\int\int\int\int &\bar{p}(x'y')\bar{p}^*(x''y'')\\ &\cdot\langle\exp ikc[\zeta(x'y't)-\zeta(x''y''t)]\rangle\\ &\cdot\exp\{ik[a(x'-x'')+b(y'-y'')]\}dx'dy'dx''dy'',\end{aligned}\tag{27}$$

which may be compared with Eq. (11). To transform this integral, it is necessary to introduce the second distribution function of $\zeta$, defined by

$$\langle F[\zeta(x'y't),\zeta(x''y''t)]\rangle=\int\int F(z'z'')W_2(z'z'')dz'dz''.\tag{28}$$

The function $W_2$ is not independent of the $x$, $y$ coordinates, even when the surface is statistically homogeneous, but then depends only on the differences $\xi=x''-x'$, $\eta=y''-y'$. Introducing the second characteristic function

$$Q_2(k',k'',\xi,\eta)=\int\int\exp[-i(k'z'+k''z'')]W_2(z'z'')dz'dz'',\tag{29}$$

Eq. (27) becomes

$$\langle I_s\rangle+|p_r|^2r_{10}^2=\int\int J(\xi\eta)Q_2(-kc,kc,\xi,\eta)\cdot\exp[-ik(a\xi+b\eta)]d\xi d\eta.\tag{30}$$

This integral cannot be evaluated w specific information about $Q_2$. If $W_2$ is t Gaussian distribution function, then

$$Q_2=\exp\{-\tfrac{1}{2}[k'^2h^2+2k'k''\Phi(\xi\eta)+k''$$

$h$ and $\Phi(\xi,\eta)$ having the same significan There is little evidence that the sea surf statistical properties implied by Eq. (31), sumption makes it possible to evaluate th Eq. (30) approximately. One then has

$$\langle I_s\rangle+|p_r|^2r_{10}^2$$

$$=(kc/4\pi)^2\int\int J(\xi,\eta)\exp\{-k^2c^2[h^2-\Phi$$

$$\cdot\exp[-ik(a\xi+b\eta)$$

and the same assumptions that previously (18) and (19) will now justify the approxir

$$J(\xi,\eta)\exp\{-k^2c^2[h^2-\Phi(\xi\eta)]\}$$

$$=J(\xi,\eta)\exp[-k^2h^2c^2]$$

$$+J(0,0)\exp\{-k^2c^2[h^2-\Phi(\xi$$

It can be shown that when this is substitu (32), the first term yields the value $|p_r|^2r_{10}$ obtains the scattering coefficient as

$$\sigma=(kc/4\pi)^2\int\int\exp\{-k^2c^2[h^2-\Phi(\xi\eta)]\}$$

$$\times\exp[-ik(a\xi+b\eta)$$

which is to be compared with Eq. (19). This now be evaluated by the method of stee which consists essentially in using the appr

$$\Phi(\xi\eta)=h^2-\tfrac{1}{2}[\alpha^2\xi^2+\beta^2\eta^2+2\gamma^2\xi\eta$$

By suitably orienting the $x$ and $y$ axes, on that $\gamma=0$; the integrals of Eq. (34) the known forms, and the final result is that

$$\sigma=(1/8\pi\alpha\beta)\exp\{-\tfrac{1}{2}[(a/\alpha c)^2+(b/\beta$$

The significant fact about Eq. (36) is th ance of the wave number $k$ from the exp scattering coefficient is independent of the of the radiation. This is characteristic of the tion of ray optics, which should, of course, short-wave radiation.[6] There is also some evidence for this independence in the case radiation scattered from the sea surface.

It remains to discuss the quantities $\alpha$ and the only parameters of the sea surface that for $\sigma$. Clearly, they are given by

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[6] Cox (private communication) has compared formulas derived entirely from ray optics. He finds should contain the additional factor $\cos^3(\mu/2)$, wher between the reflected (scattered) ray and the presumably indicates the inherent error of the prese since Eqs. (4) and (6) could justifiably be mod introduce such factors.

$$\alpha^2 = -\Phi_{\xi\xi}(0, 0), \quad \beta^2 = -\Phi_{\eta\eta}(0, 0);$$

orientation of the axes is such that

$$\gamma^2 = -\Phi_{\xi\eta}(00) = 0.$$

$$ {}_\xi(\xi, \eta) = (\partial/\partial\xi)\langle\zeta(xyt)\zeta(x+\xi, y+\eta t)\rangle$$
$$= \langle\zeta(xyt)\zeta_x(x+\xi, y+\eta, t)\rangle;$$

by $x-\xi$, $y$ by $y-\eta$, this leads to

$$\Phi_\xi(\xi\eta) = \langle\zeta(x-\xi, y-\eta, t)\zeta_x(x, y, t)\rangle,$$

$$\Phi_{\xi\xi}(\xi\eta) = \langle\zeta_x(x-\xi, y-\eta, t)\zeta_x(x, y, t)\rangle,$$

ally

$$\alpha^2 = \langle[\zeta_x(xyt)]^2\rangle, \tag{37}$$

say that $\alpha$ is the rms value of $\partial\zeta(x, y, t)/\partial x$. ne way, $\beta$ is seen to be the rms value of the e sea surface in the $y$ direction.

nus lead to the disappointing conclusion that short-wave radiation will give much less information about the sea surface than long-wave radiation. The former yields only the values of $\alpha$ and $\beta$, and the orientation of the special axes here used; the latter yields the more interesting function $\Phi(\xi, \eta)$. It is true that, by introducing ray optics from the beginning, somewhat more information can be obtained, but it is apparently not possible to find $\Phi$ nor any information about $W_2$ from experiments of this sort with short waves. This is almost the reverse of the situation encountered in atomic and molecular physics, where the scattering of radiation whose wavelength is less than the dimensions of the scattering structure yielded much more information than did the longer waves. The reason is to be found in the way the rms height of the waves enters the formulas. The (slightly) analogous parameter in crystallographic work is the rms thermal displacement of the molecules, and this is small compared to the usual x-ray wavelengths employed. Thus, the two situations are not fundamentally different, but the quantitative relations between the parameters lead to the differing conclusions.

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626

# Synonymy of the Bathypelagic Fish Genus *Rhynchohyalus*, Referred to the Expanded Family Argentinidae[1]

CARL L. HUBBS

THE contribution by Marion Grey in Copeia (1952 (2): 87–90, fig. 1) on the characters and relations of the aberrant bathypelagic fish genera *Dolichopteryx* and "*Ophthalmopelton*" prompts this supplementary discussion. Recent mid-water collecting by the Scripps Institution of Oceanography and the United States Navy Electronics Laboratory has yielded what appear to be several species of *Dolichopteryx* and probably related genera. Preliminary examination of this material and of the pertinent literature throws some light on the interesting uggestions offered by Mrs. Grey.

## Genus *Rhynchohyalus* Barnard

*Hyalorhynchus* (*nec* Ogilby, 1910).—Gilchrist and von Bonde, 1924: 4 (original diagnosis; haplotype, *H. natalensis*, new species).

*Rhynchohyalus.*—Barnard, 1925: 130 (description; relations; *Hyalorhynchus* preoccupied). Chapman, 1942b: 272, 301 (classification). Smith, 1949: 97 (diagnosis). Grey, 1952: 88 (classification).

*Ophthalmopelton.*—Maul, 1946: 62 (characterization, that of new species *O. macropus*). Grey, 1952: 88–89 (comparison and classification).

I see nothing in the descriptions or figures of the 3 reported specimens that definitely indicates generic distinction and therefore feel obliged to synonymize *Ophthalmopelton* with *Rhynchohyalus*.

### *Rhynchohyalus natalensis* (Gilchrist and von Bonde)

*Hyalorhynchus natalensis.*—Gilchrist and von Bonde, 1924: 4, pl. 1, fig. 1 (description of specimen from Sta. 530, South African Marine Survey, 135 fathoms).

*Rhynchohyalus natalensis.*—Barnard, 1925: 130 (diagnosis; type was from off Table Bay, South Africa, not Natal). Smith, 1949: 97 (diagnosis). Grey, 1952: 88 (classification; very similar to *O. macropus*).

*Ophthalmopelton macropus.*—Maul, 1946: 62–65, fig. 23 (description of specimen, from stomach of tuna, brought by fisherman to Museu Municipal do Funchal, Madeira; compared only with *Macropinna microstoma*). Grey, 1952: 88–90, fig. 1 (description of specimen from Bermuda, in open net hauled in about 300 fathoms; comparisons; relations).

The only suggestions of distinction lie in the lower number of dorsal and anal rays and the toothless jaws attributed to the type specimen of *H. natalensis*. The counts require confirmation. The teeth are small and the front of the head is indicated by the figure to have been badly damaged in the type.

## RELATIONS

Diverse views have been expressed on the relations of *Rhynchohyalus*. Gilchrist and von Bonde, without remarks, placed the genus in the Salmonidae. In the Zoological Record for 1925 and 1926 Norman listed it under the Argentinidae. Barnard compared it with *Winteria* and provisionally placed both genera in the "Microstomidae." Chapman created for these two genera a new family, Winteriidae, which he included in Berg's suborder Opisthoproctoidei of the Clupeiformes (= Isospondyli). Maul, on the contrary, referred *Ophthalmopelton*, though it is a synonym of *Rhynchohyalus*, to the Macropinnidae. Mrs. Grey accepted Chapman's views, with the further suggestion that "the general resemblance of larval specimens of *Macropinna* to *Ophthalmopelton* and *Rhynchohyalus* suggests a possible close relationship between the

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 625.

Macropinnidae and the Winteriidae." She further stressed the close similarities in external characters between *Dolichopteryx* and *Ophthalmopelton* as indicative of probable close relationship (in line with a more tentative suggestion by Chapman). I confirm Mrs. Grey's discovery of scales and adipose fin in a species of *Dolichopteryx* seemingly related to *D. longipes* and suspect that *Rhynchohyalus* is not very widely separated generically from such a dolichopterygid.

External characters seem to link the following genera into a rather tight chain: *Dolichopteryx* ⟶ *Rhynchohyalus* ⟶ *Macropinna* ⟶ *Monacoa* ⟶ *Opisthoproctus*. It would seem proper to refer the whole series to a single family, including the recently named nominal families Macropinnidae (Chapman, 1939), Dolichopterygidae (Berg, 1940), and, presumably, Winteriidae (Chapman, 1942b).

I venture an even broader recommendation, namely, that we include in a single family, Argentinidae, not only the families just listed, but also the other "Opisthoproctoidei," as delimited and characterized by Chapman (1942a, 1948, and other papers). The features that integrate this series seem more numerous and more significant than those that are used to separate the several small families currently recognized. The distinguishing features are largely those of such extreme specialization and degeneration as are characteristic of bathypelagic types. The relationships would seem best expressed by including within the Argentinidae the following recognized families (with constituent genera, in addition to *Rhynchohyalus*, discussed above): Bathylagidae (*Bathylagus* Günther and *Leuroglossus* Gilbert); "Microstomidae," more properly spelled Microstomatidae (*Nansenia* Jordan and Evermann, including *Bathymacrops* Gilchrist and *Euproserpa* Fowler; and *Microstoma* Cuvier, probably including *Halaphya* Günther); Xenophthalmichthyidae (*Xenophthalmichthys* Regan); Dolichopterygidae (*Dolichopteryx* Brauer[2]); Winteriidae (*Winteria* Brauer); Macropinnidae (*Macropinna* Chapman); Opisthoproctidae (*Monacoa* Whitley = *Grimaldia* Chapman, preoccupied, and *Opisthoproctus* Vaillant). Little seems to be gained by multiplying the monotypic and oligotypic families within an assemblage so probably natural and so basical
compact.

If the family Argentinidae would thus
expanded, there would be little reason to reta
the "suborder Opisthoproctoidei," which w
originally based by Berg (1940) on the Opisth
proctidae alone, for the two groups would be
equal coverage. Furthermore, it seems inco
gruous to base the group name on the mo
bizarre type.

In its radiation, particularly toward shor
bodied genera with very highly specialize
body form, the Argentinidae (*sensu lat*
parallel the stomiatoid series Gonostomatina
⟶ Maurolicinae ⟶ Sternoptychinae, whic
because of connecting links, I would also refe
as earlier authors did, to a single famil
Sternoptychidae.

## LITERATURE CITED

BARNARD, K. H. 1925. A monograph of th
marine fishes of South Africa. *Ann. S. Afr. Mus*
*21: 1–418, figs. 1–18, pls. 1–17.*

BERG, LEO S. 1940. Classification of fishes, bot
recent and fossil. *Trans. Inst. Zool. Acad. Sc*
*URSS, 5(2): 87–517, figs. 1–190* (photolith
graphed by Edwards Bros., Ann Arbor, Mich
gan, 1947).

CHAPMAN, WILBERT MCLEOD. 1939. Eleven ne
species and three new genera of oceanic fish
collected by the International Fisheries Com
mision from the northeastern Pacific. *Proc. U.*
*Nat. Mus., 86: 501–42, figs. 58–70.*

——— 1942a. The osteology and relationshi
of the Argentinidae, a family of oceanic fishe
*Jour. Wash. Acad. Sci., 32: 104–17, figs. 1–8.*

——— 1942b. The osteology and relationship
the bathypelagic fish Macropinna microstom
*Ann. and Mag. Nat. Hist., (11) 9: 272–30*
*figs. 1–9.*

——— 1948. The osteology and relationships
the Microstomidae, a family of oceanic fishe
*Proc. Calif. Acad. Sci., (4) 26: 1–22, figs. 1–12.*

GILCHRIST, J. D. F., AND M. A. VON BONDE. 19
Deep-sea fishes procured by the S. S. "Pickle
(part II). *Union S. Afr. Fish. and Mar. Bi*
*Surv., Rept. 3 (1922), Spec. Rept. 7: 1–24, pls. 1–*

GREY, MARION. 1952. First record of the dee
sea fish *Dolichopteryx longipes* from the Paci
with notes on *Ophthalmopelton macropus*. COPEI
*1952 (2): 87–90, fig. 1.*

MAUL, G. E. 1946. Um novo género e espéc
dos macropinídeos. *Bol. Mus. Municipal Funch*
*2: 62–65, fig. 23.*

ROULE, LOUIS, AND FERNAND ANGEL. 193
Larves et alevins de poissons provenant d
croisières du Prince Albert I$^{er}$ de Monaco. *R*
*Camp. Sci. .... Albert I$^{er}$ .... Monaco, 7*
*1–148, pls. 1–6.*

SMITH, J. L. B. 1949. The sea fishes of southe
Africa. *Central News Agency, [Capetown,] Sou*
*Africa: xvi + 550, 519 figs., 105 pls.*

SCRIPPS INSTITUTION OF OCEANOGRAPHY, UN
VERSITY OF CALIFORNIA, LA JOLLA, CALI-
FORNIA.

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[2] *Dolichopterygiella* Roule and Angel (1930: 69–76, pl. 4, figs. 90–98) was proposed as a name for a larval type and therefore has no nomenclatorial standing.

Reprinted from COPEIA, 1953, No. 3, dated August 26, pp. 193-194.

IDENTIFICATION AND RELATIONSHIPS OF THE ANCHOVY DESCRIBED FROM CALIFORNIA AS *ANCHOVIA SCITULA*.[1]—Species known only from type descriptions are always bothersome, particularly when they were described from regions where the fauna has been exhaustively studied. Of such species in the California marine fauna one of the most troublesome was described by Fowler (1911, Proc. Acad. Nat. Sci. Phila.: 211–12, fig. 2), on the basis of one specimen (A.N.S.P. No. 1576) recorded as having been collected at San Diego by W. N. Lockington. Under the name *Anchoviella scitula*, the species was accepted as valid by Jordan, Evermann, and Clark (1930, Rept. U. S. Comm. Fish., 1928, pt. 2: 49) and by Hildebrand (1943, Bull. Bingham Oceanogr. Coll., 8 (2): 109–12, 118–19, fig. 50). After studying and redescribing the holotype, Hildebrand concluded that the species approaches *Anchoa* and that it seems to be most closely related to *Anchoa exigua*. He added that "the specimen on which this species is based seems to be as unique to the fauna of the Pacific Coast of the United States as *Anchoa duodecum* [*sic*] is to the Atlantic." McHugh and Fitch (1951, Calif. Fish and Game, 37: 494–95), in reopening the problem, have commented on the possibility that the type may be an aberrant example of *Engraulis mordax* Girard. "It seems highly unlikely," they concluded, "that the species is valid."

A reexamination of the evidence convinced me that the type can not be an example of *Engraulis mordax*, for the pelvic and anal fins are much too far forward, the caudal peduncle much too long, the maxillary much too short and too rounded, the pectoral axillary scale much too short, and the gillrakers and scales as well as the anal rays too few. Dr. Robert R. Harry, in kindly determining that the type has 4 short but well developed rakers in the posterior series of the upper limb of the third arch, where *Engraulis mordax* has none, has provided the data that clinch the decision.

It is clear from a study of Hildebrand's key (pp. 109–11) to the species of *Anchoviella* that the type of *scitula* fits into items a, b, cc, e, and f. Under f there are recognized, in addition to *scitula*: (1) *A. perfasciata* (Poey) of the Atlantic, which has the axillary scale much longer, the anal fin much farther back, and the rakers somewhat more numerous; (2) *A. brevirostris* (Günther) of Amazonian fresh waters, a deeper-bodied fish with fewer pectoral rays; and (3) *A. miarcha* (Jordan and Gilbert), known only from young to half-grown specimens, 28 to 45 mm. long, from Mazatlán to Panamá and apparently from the Galápagos Islands. The only differences of importance between *scitula* and *miarcha*, as described by Hildebrand, are the higher number of rakers (15 to 18 + 23 rather than 12 to 14 + 18 to 20), the shorter head (4.4 versus 3.8 to 4.1), and the larger eye (3.4 versus 4.6 to 5.5). The differences in proportion may be explained by age variation, for the specimens of *miarcha* are not much beyond the postlarval stage, which in anchovies is small-eyed, and, in specimens equally large (97 mm. to end of broken caudal fin, 84 mm. to base of caudal), the head would probably have decreased in relative size to the values shown by the type of *scitula*. Similar age changes in the relative sizes of the eye and the head may be observed in other species: for example, in series of *Anchoa mitchilli mitchilli* (Valenciennes) from New York the head measures 3.6 to 4.0 into the standard length in large young and half-grown, 4.0 to 4.4 times in adults, and the eye enters the head 4.3 to 5.0 times in the smaller specimens, 3.6 to 4.4 times in the larger. It is highly probable that the discrepancy in raker number can also be explained. There is presumably some increase in number with age, as I have noted in several species of anchovies and as McHugh (1951, Bull. Scripps Inst. Oceanogr. Univ. Calif., 6: 148–50, fig. 5) has proved to be maintained throughout life in *Engraulis mordax*. Furthermore, the type of *scitula* may have rakers near the maximum number for the species it represents. Since only 1 and 6 counts are given for the respective nominal species, it is to be expected that in large series of counts, values as high as those of the type of *scitula* will be obtained in adults of *miarcha*.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 626.

It is concluded that *Anchovia scitula* Fowler was based on an adult specimen of *Anchoviella miarcha* (Jordan and Gilbert). This interpretation removes the doubt that Hildebrand felt regarding the generic reference of *miarcha* to *Anchoviella* and renders it unlikely that its resemblance to *Anchoa exigua* is an indication of close relationship. Though additional morphological differences would be very welcome, it seems that Hildebrand's distinction of *Anchoviella* and *Anchoa* is justified, particularly in view of the different centers of geographic and ecological distribution.

It seems probable that *Anchoviella miarcha* occurred in southern California during the warm period of the middle 1800's (Hubbs, 1949, Jour. Mar. Res., 7, 1948: 459–82, figs. 1–6) and was still at San Diego when Lockington collected a specimen there about 1880. It is possible, however, that the type of *Anchovia scitula* was taken by Lockington in the Gulf of California, where he is known also to have collected. There is a remote possibility that it represents a form, probably now extinct, that was differentiated subspecifically or specifically from *A. miarcha*.

It seems almost certain that *Anchoviella miarcha* no longer occurs in or near California. No specimens have been secured in the extensive recent collecting along the coasts of southern California and of western Baja California, by the California Department of Fish and Game and by Scripps Institution of Oceanography (McHugh and Fitch, *loc. cit.*), and in the Gulf of California, by Boyd W. Walker and students of the University of California at Los Angeles (I am grateful to Dr. Walker for this information). The range of the species seems to ha become contracted to more tropical waters.

The genus *Anchoviella* as a whole, contrasti with *Anchoa*, is primarily South and Central Am ican and is chiefly fluviatile (Hildebrand, *loc. cit* The only other species known from north of Ce tral America are *A. parri* Hildebrand, of the G of California, which has more anal rays th *A. miarcha* (23 to 26; the figures misplaced in Hild brand's tabulation on p. 111); *A. analis* Miller (194 Jour. Wash. Acad. Sci., 35: 265–67, fig. 1), a ve different species from Laguna de Mexcaltita Nayarit, México; *A. perfasciata* (Poey), of the We Indies; and the species described by Swain a Meek from Woods Hole, Massachusetts as *Sto phorus eurystole*, and generally identified with *E graulis argyrophanus* Kuhl and van Hasselt ( Valenciennes, 1848, Hist. Nat. Poiss., 21: 49–5 from the equatorial Atlantic. The last species, sporadic occurrence along the Atlantic Coast of t United States, seems to parallel *A. miarcha* some distributional respects. It presumably al has a permanent abode in more tropical water Hildebrand (*loc. cit.*: 109–18) failed to separa it conclusively from the species that he describ from Venezuela as *A. estauque*. This name should spelled *estanquae*, because the new rules of nome clature demand the correction of erroneous spellin derived from misread labels (Schultz, 1949, Pro U. S. Nat. Mus., 99: 47–48, indicated the corre spelling of the type locality to be Estanques Bay Whether this Atlantic relative of *A. miarcha* shou be known as *A. eurystole* (Swain and Meek) or *A. argyrophanus* (Kuhl and van Hasselt) can n be ascertained without an examination of the typ of *argyrophanus*. This species has occurred as f north as Lynn Harbor, Massachusetts, where seined a 51-mm. specimen (U.M.M.Z. No. 14064 in August, 1928.—CARL L. HUBBS, *Scripps Instit tion of Oceanography, University of California, Jolla, California.*

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VOL. 37, NO. 5 (MAY, 1953), PP. 1067-1074, 5 FIGS.

# DISTRIBUTION OF SURFACE TURBIDITY OFF MISSISSIPPI DELTA[1]

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## ABSTRACT

Aerial and surface observations around the Mississippi Delta show a great quantity of suspended sediment in the water close inshore. The amount of material in suspension, controlled chiefly by volume of river flow and distance from source, in general decreases to a small value a few miles off shore, but under certain conditions turbid water extends to sea for distances of at least 65 miles as long plumes off the mouths of the important passes. Most of these plumes have relatively sharp boundaries. The direction of seaward distribution of the turbid plumes is controlled chiefly by the wind and to less extent by semi-permanent currents, tidal currents, and by river flow. The intensity of surface turbidity generally can be correlated with the rate of deposition in any area.

## INTRODUCTION

One of the important phases of the study of recent sediments of the Mississippi River Delta, being conducted by the Scripps Institution of Oceanography, has been the investigation of the circulation and physical properties of the water adjacent to the delta. The turbidity caused by the outpouring of large volumes of suspended material by the river is an important water property because of its effect on sedimentation. Knowledge of the fate of this material after it leaves the river is fundamental to the general problem of sediment study in the area. The purpose of this report is to give a preliminary description of the general distribution of surface turbidity.

During the initial field seasons in Breton Sound and the region off Main Pass and Pass a Loutre more than 300 secchi disc observations for determining distribution of turbidity were made. These were supplemented by 32 quantitative determinations of the amount of suspended material in the water made under various conditions during the months of October, November, and December, 1951. These investigations were carried out aboard a surface vessel. As the work progressed it was apparent that wider coverage was necessary than could be obtained with this method. The instability of flow features in the inshore area causes a great variation in physical properties at any one point, and the turbidity extends for a considerable distance seaward. These factors make impossible critical synoptic observations over a large area from a slow-moving boat. In order to overcome this difficulty, an airplane flight was taken over the entire area to study and map the distribution of the turbidity. Many of the observations on which the following discussion is based were made on this flight during which a broken ceiling at about 2,000 feet limited the altitude of observation, and a light ha somewhat restricted visibility.

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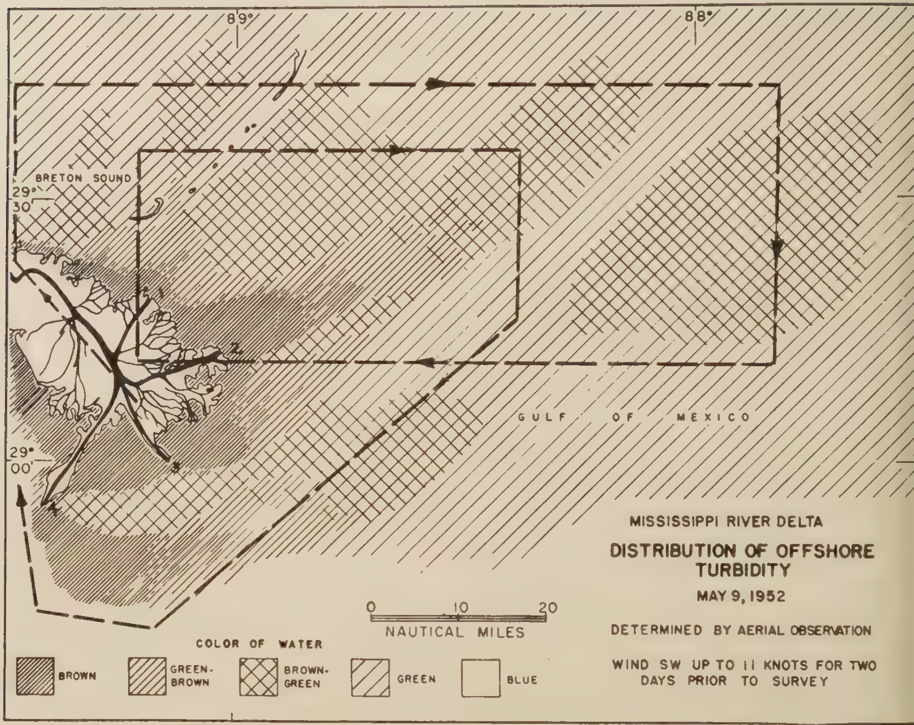
[2] Scripps Institution of Oceanography.

Appreciation is extended to Gerhard Herzog and The Texas Company for making the plane available. Thanks are also due the pilots, M. A. Fuori and F. H. Foreman, for their assistance in providing location data and for their helpful suggestions. F. P. Shepard aided greatly both with field observations and in the preparation of the manuscript.

## OBSERVATIONS

*General distribution of turbidity.*—A chart was prepared to show the salie features of the distribution of turbidity from observations made during the flig (Fig. 1). Patterns are used to represent water colors which could be recogniz readily from the air and which have significance as indicators of amount ar average size of suspended matter. It will be seen from Figure 1 that the brow highly turbid waters are disposed halo-like around the shoreline with pronounc outward bulges off the mouths of the active passes. These bulges are prolong northeast and grade in color from brown to green as the amount and size suspended particles become smaller. Because the color change is gradual alo the axis of elongation and is much sharper transverse to this axis, the turb clouds have a plume-like appearance. The blue water shown south of the more less turbid area is undiluted open gulf water (Fig. 2).


89°
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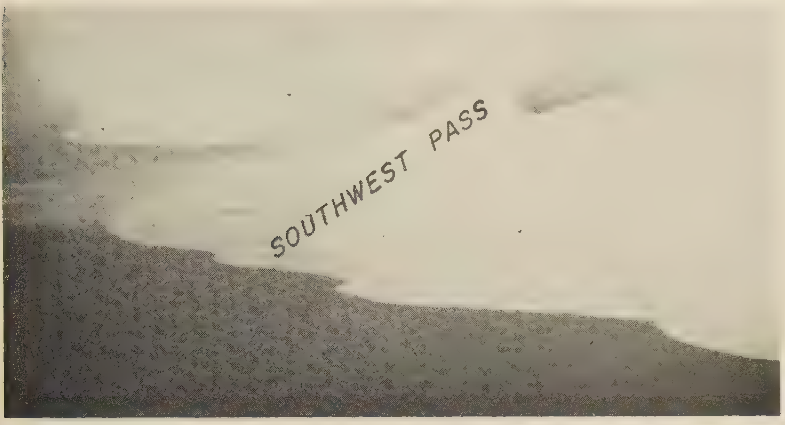
GULF OF MEXICO
MISSISSIPPI RIVER DELTA
DISTRIBUTION OF OFFSHORE TURBIDITY
MAY 9, 1952
0 10 20
NAUTICAL MILES
DETERMINED BY AERIAL OBSERVATION
WIND SW UP TO 11 KNOTS FOR TWO DAYS PRIOR TO SURVEY
COLOR OF WATER
BROWN
GREEN-BROWN
BROWN-GREEN
GREEN
BLUE

FIG. 1.—Distribution of offshore turbidity, Mississippi Delta, May 9, 1952. 1: Main Pass. 2: Pass a Loutre. 3: South Pass. 4: Southwest Pass. Arrows: course of flight.



G. 2.—View from 1,500 feet, showing sharp contact between Gulf and River water off Southwest ass. Looking north. Note position of Southwest Pass and easterly movement of main mud plume.

The distance to which these plumes can be traced northeast is determined by e amount of suspended material and is roughly a function of the volume of ver water carried by the passes off which they are found. This relationship does ot hold entirely because of a tendency toward downstream coalescence between e plumes associated with passes which normally discharge toward the east.

*Inshore turbidity.*—Near a pass mouth during the low-water season the mount of sediment in suspension in the surface layer was found to be around .260 gram/L. This value decreased by approximately $\frac{2}{3}$ within 5 miles off the outh in the main direction of current flow. Outside of the main stream of flow ithin 5 miles of the source the amount of material in suspension was less than of the value in the pass mouth. High winds blowing over areas of shallow bottom also greatly influence the turbidity. As much as 0.640 gram/L. of suspended

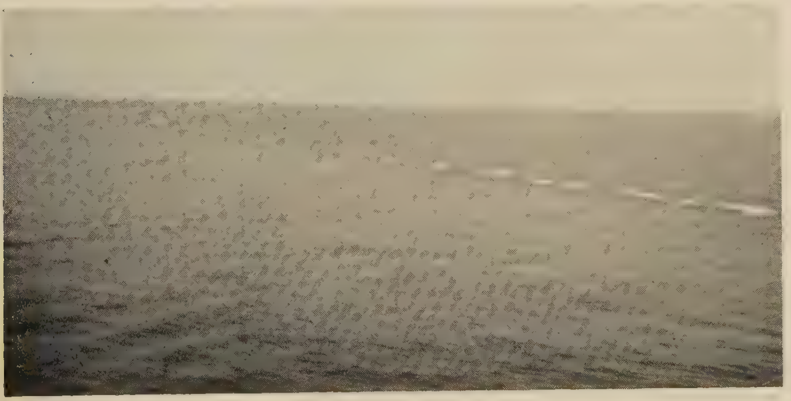


FIG. 3.—Typical foam (convergence) line as seen from a vessel. Water mass in foreground is flowing over water in background.

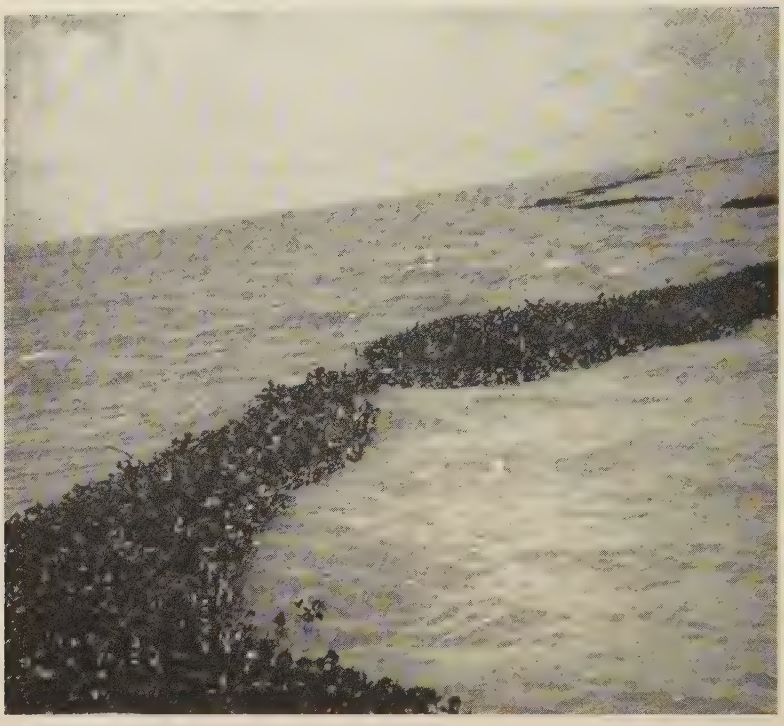


FIG. 4.—Convergence line marked by water hyacinths. Water at right flowing over water on left.

sediment has been measured in such areas during a storm period where normal values during calm weather and similar low-river discharge are no greater than $\frac{1}{100}$ of this. These values are given to indicate the amount of suspended material which occurs and to illustrate the great variation which may be found laterally and with changes in weather conditions.

Besides the extremely high turbidity, the most prominent features of inshore turbidity distribution are the sharp contact zones between water masses of somewhat different color (Fig. 2). Ordinarily these zones are heavily flecked with foam and often have entrained large quantities of floating débris such as twigs, logs or water hyacinths (Fig. 3, 4). The terms "foam lines" or "convergence lines" have been adopted for these features in this report and are used interchangeably "Foam line" is a simple descriptive term which implies no causal agent. The features appear to be lines of convergence associated with movement of one water mass over an adjacent water mass, so that the term "convergence line" seems justified.

As observed from a surface vessel foam lines generally appear to be long sharp, essentially straight lines of demarcation between water types. From the air, however, they are seen to be sharp lines with minor sinuosities superimposed on larger-scale curvature and which vary in length from approximately 1 to 2 miles. The radius of curvature ordinarily is large and may be reversed in some cases.

Convergence lines are most commonly seen in the brown and green-brown water surrounding the active pass mouths where velocity and density differences between adjacent water masses frequently are large. As many as three lines of various lengths have been observed distributed roughly concentric to a pass mouth. Where several occur in one area they appear to be moving in the same approximate direction in a sector and can be discerned because of a decrease in turbidity behind the maximum at the leading edge, the line of active convergence. These concentric foam lines seem to be produced by more or less random pulsations in volume of river discharge. Such pulsations may be caused by real variation in river transport, short term irregularity in the tidal curve, or seiches or other standing waves in the basin receiving the river discharge. Foam lines also extend in a direction sub-parallel with an axis of flow as through a tidal pass between islands

Foam lines are normally continuous without a break throughout their length, but occasionally the sharp contact is blurred and gradational for short distances. The gradational contact, rarely seen along the length of an active convergence, in many places is observed for a considerable length at either extremity of the line. This seems to be a demonstration of the manner of foam-line decay. It appears that the forces which produce active convergence diminish in intensity until the moving foam line, normally undergoing some decay at the extremities, can no longer be maintained. When the advance of the foam line ceases, diffusion instead of convergence becomes the dominant process at the interface, causing the disappearance of the sharp boundary, and the development of a narrow zone of contact replacing the sharp linear boundary.

*Offshore turbidity.*—Certain other features are more peculiar to the offshore turbidity distribution. The long plumes of sediment which extend seaward from the major passes generally remain connected with their source as long as active seaward dissemination of suspended matter is occurring in a specific direction. When the direction of sediment dispersal is altered, isolated areas of turbidity may persist for a time in the distal part of the decaying plume because of low particle settling velocity. The outlines of the plume tend to remain more or less distinct, while within the plumes there is a seaward color change accompanying the net loss of sediment. This color change may be either gradational or associated with minor foam lines. At the outer extremity, the plumes blend with the adjacent water and no longer can be distinguished.

Large detached masses of faintly turbid water may be developed under certain conditions. One of these masses is indicated in Figure 1. The origin of this turbid water is not certain. It may be a mass detached from the plume on the west by large-scale horizontal eddying like that found along the Gulf Stream, or, as previously suggested, it may be preserved from a previous introduction of turbidity to the area by the low settling velocity of its particles.

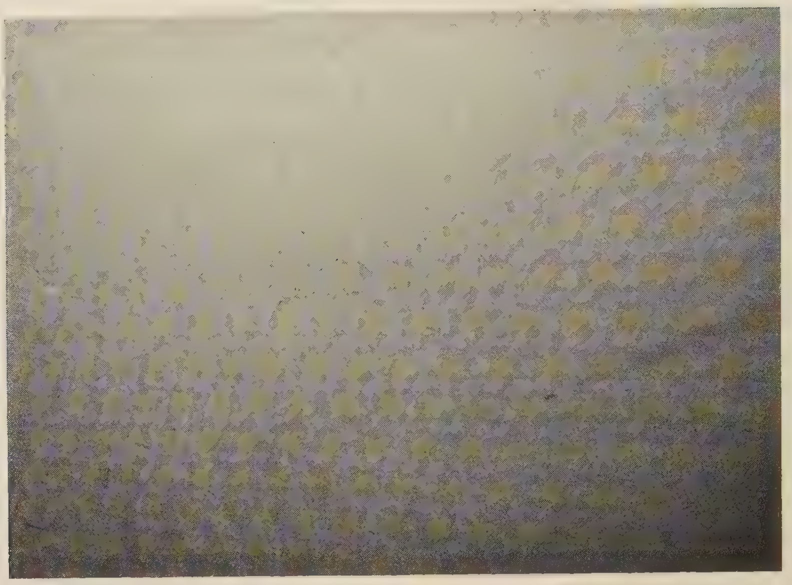


FIG. 5.—Turbidity distribution offshore. Note long rows of highly turbid water (gray streaks in photograph); also clearer water stirred up in wake of vessel.

Another feature of the offshore turbid zones, which apparently develops only under specialized conditions, is the formation of a surface pattern like the pattern of light often seen on the bottom of a gently disturbed swimming pool. This surface pattern is produced when long parallel ribs of turbid water are separated by bands of clearer water. When two or more of these trains of ribs, extending at an angle to each other are superimposed, a pattern of crudely shaped, diamond-like figures results which is very striking when seen from the air (Fig. 5). This pattern, when located on the margin of a plume, produces a feathered contact zone between adjacent water masses. Ewing (1950) has investigated surface slicks which occasionally form a similar ribbed pattern and demonstrated their relationship to internal waves at a shallow interface between waters of different densities. The ribbed distribution of turbidity off the Mississippi Delta may be a feature similar in origin due to waves at the interface between low-density surface water and more saline water beneath, and must play a considerable part in the diffusion of the turbid mass. Decay of the feathered contact would produce the normal gradational contact.

*Thickness of surface turbid zone.*—The turbid mass of water off a large river debouching into the sea often has been termed a "wedge." This word does not convey an accurate description of the vertical distribution of the turbidity. A more accurate term would be a "stratum" of turbid water, since the vertical dimension is insignificant when compared with the horizontal extent. The maximum thickness of the turbid, fresh-water, surface layer in an undredged pass mouth during low-water stages is about 5 feet and is somewhat thicker than this in the deeper dredged channels. During periods of high river discharge the thickness of the surface layer is increased somewhat, but the presence of living marine fish on the bottoms indicates the existence of a thin saline layer at the bottom even under these conditions. All observations in the area show that the surface layer thins rapidly from the maximum in pass mouths to a thickness of 1½–3 feet and retains approximately this thickness over large areas while mixing with the underlying saline water. Because the surface layer is the zone from which the settling of suspended particles is initiated, the water beneath is charged with material in suspension, the degree depending to a large extent on the turbidity of the surface layer and the flow characteristics of the two layers. Close inshore the high turbidity commonly extends through the entire water column with maxima occurring at the surface and toward the bottom. Farther offshore where color and intensity of turbidity indicate the amount and average grain-size of material in the surface layer have decreased, the subsurface waters also are somewhat turbid, but the difference between the waters above and those beneath may be more visible than inshore. This seems to be the condition where surface vessels churn up relatively clear water from beneath a more turbid surface layer (Fig. 5). Still farther offshore the interface below the surface stratum becomes more and more diffuse as vertical mixing progresses until a distinction ceases to exist.

*Agents of turbidity distribution.*—The agents which bring about the observed direction of turbidity distribution are wind and currents. In the inshore areas a residuum of river velocity carries the fresh water over the more saline water beneath. Tidal currents which are active on the eastern side of the delta modify these original surface currents and, aided by the wind, deliver the turbid water to offshore areas.

It is difficult to determine the relative importance of wind and permanent currents in distributing the offshore turbidity. The Current Chart for the Gulf of Mexico (H.O.Misc. 10,690–5) shows a slow north-northeast current in the observation area during May. All field experience in the area, however, indicates that this current, if present, must be weak and sporadic. Good correlation between the direction taken by the turbid plumes and the wind direction for several days previous to the flight and the field experience of the project party strongly suggests that the wind is the more important agent in controlling direction of turbidity distribution. F. P. Shepard, during a flight from Tampa, Florida, to New Orleans in February, 1952, observed the northern margin of a plume 40 miles east of the delta following a protracted northwest blow. The Texas Company pilots report large turbid plumes which extend far west along the coast during periods of easterly wind. These separate observations are taken as corroborative evidence for these conclusions.

## GEOLOGIC SIGNIFICANCE

The rate of deposition of sediment around the Mississippi River Delta is largely a function of the volume of sediment in suspension in the surface layers.

Figure 1 shows the highly turbid zones to be restricted to the nearshore areas, condition which generally prevails. Depth changes which have occurred in th last 90 years show that the area covered by brown water is the locus of maximu deposition. In addition, complete penetration of the recent delta mud by core within 11 miles east of the coast shows that the rate of deposition falls off ver sharply with increasing distance from shore. These cores contain coarse, mudd sand at a depth of 7 feet below the bottom which is unlike the soft fine-graine foraminiferal clays currently being deposited in this region. If volume of sedimen introduced by the river remains constant over a period of time, the amoun of sediment deposited at a particular point in this period must be determine in part by the distance from the river mouth and the prevailing direction an strength of the wind, since these factors are important in controlling the distribution of surface turbidity. The effect of subsurface marine currents play a part in modifying suspended sediment distribution prior to deposition. A departure from the thickness of deposits which might be predicted from consideration of the factors of wind, volume of sediment introduced, and distance fro source must be some measure of the effectiveness of these marine forces to alte the inferred distribution.

## SUMMARY AND CONCLUSIONS

1. Suspended sediment introduced into the Gulf of Mexico by the Mississipp River may extend at least 65 miles seaward from the delta.

2. The direction of distribution of the turbidity is controlled chiefly by th wind, and to a lesser extent by semi-permanent and tidal currents and a residuu of river flow, whereas the amount of suspended material present under norma wind conditions is largely a function of volume of river outflow and distance fro river mouths.

3. Muds and clays of Mississippi River origin may be expected over a wid area to a thickness which is related to the distance from the source and the statistical distribution of wind force and direction as modified by marine currents

## REFERENCES

"Central American Waters Current Chart" (1952). *H. O. Misc. Pub. 10,690–5* (May).
Ewing, G. C. (1950), "Slicks, Surface Films, and Internal Waves," *Jour. Marine Research,* Vol. pp. 161–87.

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# FREE-DIVING: A NEW EXPLORATORY TOOL

By WILLARD N. BASCOM and ROGER R. REVELLE
Scripps Institution of Oceanography, University of California

One rather obvious way to increase the efficiency of oceanographic measurements is to use better adapted instruments which increase the information rate. The first step is a simple point measurement of one phenomenon at one instant, such as is made by a thermometer; the next step is a measurement at one point extending over a length of time, like that made by a wave meter, or a measurement over a distance in a very short time, as by the bathythermograph. These instruments give a one-dimensional, time or distance, measurement. Areal, or two-dimensional measurements can be made by an array of instruments, three dimensions come from photographs, and the underwater motion picture camera supplies the greatest amount of information, since it stores some three-dimensional information over a period of time. Underwater television, the most promising tool of the future, is still far from the stage of development where it can be used operationally on oceanographic research ships.[1]

However, there is now at the command of the inshore oceanographer a tool which, to depths of 60 meters, allows an immeasurably higher level of observation, sampling, and measurement than any combination of mechanical devices. This fabulous instrument is the scientist himself equipped with SCUBA (self contained underwater breathing apparatus). Do not dismiss the SCUBA apparatus as a mere modification of the old diving suit; it is much more than that, for with it man becomes part of the medium (Fig. 1). Subject to the same forces, he partakes of the feelings of the other underwater animals as he is swayed by passing waves and drifts along, weightless, with the ocean currents. From the surface the investigator dangles on cable instruments which, at best, is a specialized sensory extension or non-selective sampler, but below the surface he is able to receive a great many kinds of information at one time. He feels the wetness and the cold—the thermocline may come as a distinct shock; he notices changes in turbidity and the associated illumination level; he sees the variations in the bottom and is able to estimate the relative areas of each type; he hears noises, sees the underwater life *in situ*, and can sample selectively. The investigator equipped with the SCUBA is thus the paragon of instruments, for the intermediate steps in the acquiring of information are performed at the site of the observation.

But men have been underwater before in diving helmets, suits, bells, and bathyspheres. What then is unique in

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[1] Underwater television and marine biology. BARNES, H. *American Scientist*, *40*, 679, 1952.

tribution from the Scripps
stitution of Oceanography
Series, No. 628

this new apparatus? It is the freedom inherent in the system; and on the underwater swimmer, who carries the equipment for an air supply, the title, "free diver" has been conferred. Equipped with the self-contained diving unit he is literally "free as a fish" as soon as he enters the water. There are no air lines, life lines, or telephone lines to slow him down and entangle him; the ship or boat need not be anchored at all (most line divers require that the diving boat have a two-point mooring); and the free diver is in no way dependent on the attention of a helper (tender) on the surface for air or information.

Thus the free diver has become a high type of underwater animal, but, like all animals, he has certain limitations. He is limited by the volume of the atmosphere which he carries in the container on his back. With intermediate volume air bottles he can stay 10 meters below the surface for over an hour, or he can stay at 30 meters for a half hour or at 60 meters for perhaps ten minutes. Experts with special equipment have gone to over 100 meters for short periods of time, but the usual range is between the surface and 40 meters (Fig. 2).

The free diver thrives in warm tropic seas where corals tell him that the temperature is above 20 °C. but often he is found making observations in the cooler coastal waters of the United States and in the Mediterranean, where the water is no more than 14 °C. For colder waters a prosthetic device is required which gives him some of the cold-resisting properties of the other swimming mammals; this artificial substitute for hair and blubber is the cold-water swim suit. With such suits free divers have been able to swim among icebergs for 15 minutes or more and do scientific work in ten-degree water.

Many kinds of free-diving breathing devices have already been built and tested in countries where military or sporting applications have created a demand. Italy, France, Sweden, England, and the United States have produced one or more types of SCUBA semi-commercially; the simplest ar most convenient of these is the Gagna Cousteau device, or *Aqualung*, which becoming widely used in the Unite States. The Aqualung furnishes the u derwater investigator with air as need from a compressed air bottle. That when the underwater swimmer needs breathe, he simply sucks air from t breathing tube, and when he exha the air is expelled through the sa mouthpiece and bubbles surfacewa Such open-circuit air devices will pro ably continue to find favor over t

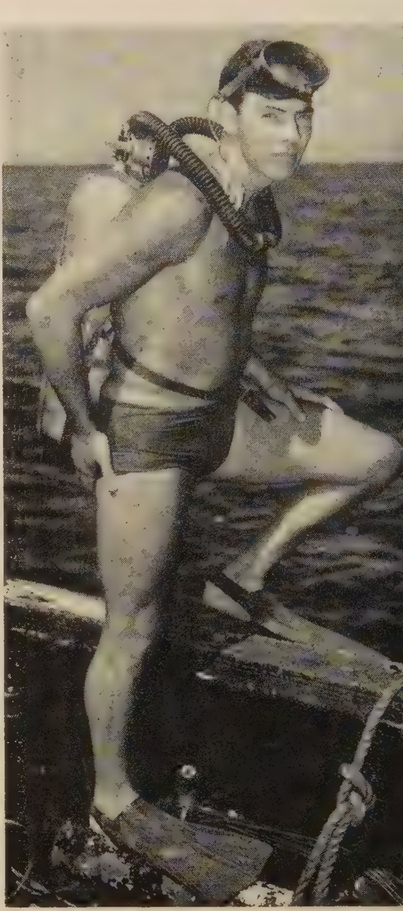

FIG. 1. Dr. Robert Livingston equipp with an Aqualung ready to go over the si of the research vessel *Spencer F. Baird.*

more complex oxygen-supplying, closed-circuit apparatus, which imposes the limitation that if used in pressures of more than two atmospheres the diver is subject to oxygen poisoning.

The Aqualung consists of two parts: the bottles of air, compressed to about 140 atmospheres, and a demand valve pressure regulator which readily attaches to the bottles and from which air is led to the mouth by means of flexible tubing. In water, this apparatus has near-neutral buoyancy and, carried on the back, does not hamper the wearer; even though it appears bulky, its drag is negligible at the ordinary swimmer velocities of less than 1.5 knots. Each complete Aqualung unit costs about $150.00 and a high-pressure compressor outfit can be obtained for less than $1000.00, a very modest price for underwater freedom. Most important; the Aqualung has the best single quality that an oceanographic instrument can possess: it requires no field adjustments or replenishments of any kind and can be kept ready for instant use for months at a time.

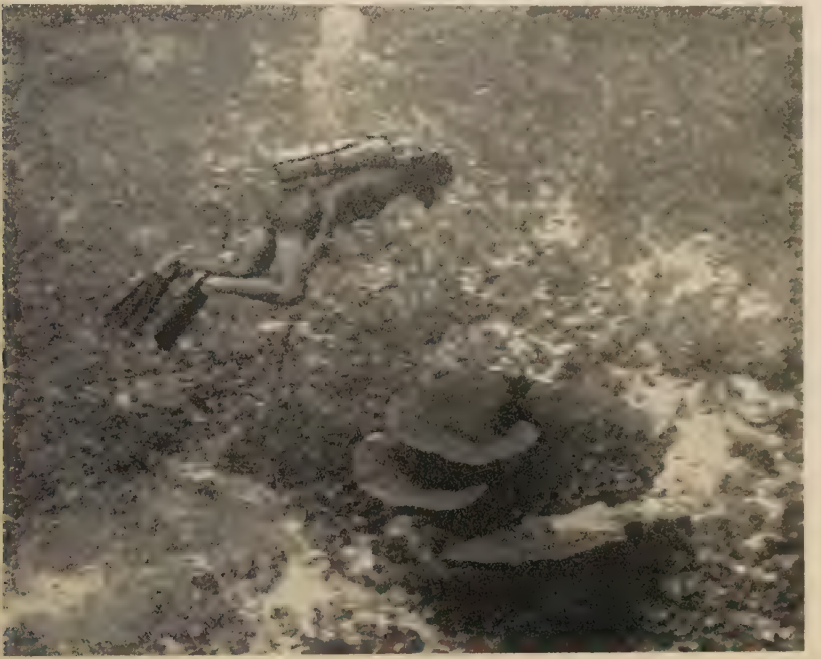

FIG. 2. Free diver, Walter Munk, motionless in water observing a giant coral on the surface of Alexa Bank: a drowned atoll whose former island crests are 120 feet below the present sea surface.

Out of his usual element, man is subject to certain physiological difficulties—and sometimes psychological ones—but once properly trained to live underwater he is as safe there as in an automobile. The diver-candidate quickly learns about nitrogen narcosis, air embolism, oxygen poisoning, bends, and certain pressure problems, and can forestall their appearance or minimize the effects. Soon he breathes without thinking about it and grunts signals to his buddy, porpoise-fashion. When confidence increases, the air supply lasts longer and useful work is done more efficiently. In concentrated lessons of two weeks or intermittent lessons of two months an investigator can become an underwater scientist. Age is apparently not a barrier if the body is willing. The best of our military swimmers are in their mid-forties; Cousteau has trained biologists in their fifties to dive to 60 meters and some Polynesians still dive for pearls at an age when our citizens retire on social security. Aside from the fact that men with a generous layer of fat can stay warm longer and that men of standard proportions can get better-fitting swim suits, there seem to be no especially advantageous body characteristics. Engineers, submarine geologists, and biologists need no longer be restrained from the water-medium by the glass walls of wave channels and aquaria; the real-life world of shallow water is now conveniently accessible.

At the Scripps Institution of Oceanography, extensive use of this new-found ability has been made in investigating shallow-water life, shoreline processes, and the nature of waves and currents. The free-diving technique has been most effective in the following applications.

1. A study of the ecology of the kelp beds at La Jolla has been in progress for about two years. Fish populations have been correlated with the harvesting of kelp, and an extensive program of underwater photography has been successful in capturing underwater scenes on film for leisurely study and classroom review.

2. Undersea instruments have been watched in operation and uncertainties that had existed were resolved. Wave meters were calibrated *in situ* and a program of the observation of coring devices is contemplated. British swimmers have photographed beam-trawls in action on the bottom.

3. Bottom currents in tidal entrances have been measured by underwater swimmers using a specially designed current meter staff, and the distribution of near-bottom velocities at a series of stations was conveniently obtained in a short time.

4. Geological observations of hitherto unexplored areas have been made. At La Jolla, the submarine canyon has been thoroughly examined and photographed by underwater swimmers. On Expedition Capricorn a sunken atoll, Alexa Bank, and a submarine volcano, Falcon Island, were studied and the several distinct underwater terrains of the atoll were compared including the otherwise inaccessible outer edge of the reef.

5. Geological mapping of undersea rocks for the purpose of extending shoreline maps seaward in the investigation of possible petroleum structures.

6. An examination has been made of the movement of bottom materials in the surf zone and their resulting structures (bars, ripple marks, rip channels).

7. The subsurface parts of shoreline structures, especially wharves and piers, have been brought under observation.

8. A study of the physiological requirements of underwater swimmers, in cooperation with the National Research Council Panel on Underwater Swimmers, has been made.

In summary, the substitution of the incomparable human senses for a blind groping with long wire fingers has created the possibility that man may gain the same level of scientific understanding in the upper part of the hydrosphere as has long been maintained in his normal land habitat.

**629**

*(Unavailable for exchange)*

Reprinted from **ANALYTICAL CHEMISTRY**, Vol. 26, Page 249, January 1954
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**atic Servo-Operated Filter Photometer.** James M. Snod-s, Dayton E. Carritt[1], and Warren S. Wooster, Scripps In-tion of Oceanography, La Jolla, Calif.

NG the most important inorganic constituents of sea water e the dissolved plant nutrients, in particular phosphate, , and silicate. All of these are commonly determined by tiometric methods. During recent years attempts have nade to adapt these methods for use with photoelectric neters. This development has been slow and rather un-ctory because of the sensitivity of most such instruments to tion of the ship.

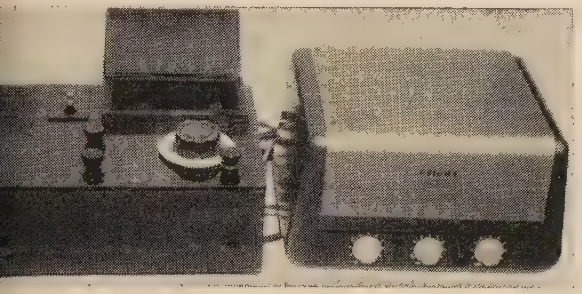

Figure 1. Filter Photometer with Amplifier

following criteria must be met by a seagoing colorimeter, tion to the usual requirements of accuracy and precision.

**ility.** Operation must be unaffected by the motion of the Because shipboard power supply is often unstable, either trument must be unaffected by fluctuations of voltage and ncy, or external provision must be made to minimize such tions.

**ability.** Despite exposure to sea air, violent motion, and treatment, the instrument must give trouble-free operation continuous use for long periods of time. It must give te and reproducible results in the hands of semiskilled per-working under adverse conditions.

**atility.** A variety of analyses may be made, involving nt wave lengths of light and different absorption paths. strument must be capable of utilizing absorption cells from cm. in length.

**ability.** Seagoing instruments may be taken on and off ship adverse conditions and are frequently used on small craft.

rvey of commercial photometers revealed only one instru-which met these criteria. The Beckman Model DU spec-tometer has been used at sea by this laboratory since 1948 s proved satisfactory for shipboard analysis. The spec-tometer, however, is slightly affected by the motion of the perhaps unnecessarily versatile for this is rather expensive, and is heavy and ly to carry.

ral photometers for use in marine chem-rk have recently been designed. Harvey *rine Biol. Assoc. United Kingdom*, 27, 948)] reported an absorption meter balanced selenium photocells, the null being determined with a galvanometer. er, he does not mention using this in-nt at sea. Ford [ANAL. CHEM., 22, 950)] describes a seagoing photoelectric eter in use at the Woods Hole Oceano-Institution and elsewhere. This in-nt uses two photocells, the light to the ng photocell being controlled by a mic aperture and the balance point ed by an electric eye tube.

automatic servo-operated filter photometer was designed to meet the need for a rugged, relatively inexpensive seagoing instrument characterized by a high degree of precision, great flexibility, and ease of operation. It operates on the double-photocell principle, a servomotor driving the main slide wire and automatically eliminating unbalance between the signals from the two photocells. The instrument has been used during the past 3 years by the Scripps Institution of Oceanography, the Chesapeake Bay Institute, and the Pacific Oceanic Fishery Investigations of the U. S. Fish and Wildlife Service, and has proved satisfactory for shipboard use.

## DESCRIPTION OF INSTRUMENT

An existing commercial photometer, the Lumetron Model 402-E colorimeter (Photovolt Corp.), was modified for automatic balancing. The electrical unbalance or error voltage between the two photocells is inverted to 60-cycle alternating current by means of a Stevens-Arnold Type 247 chopper and Triad G-10 transformer. The low level alternating current from the chopper is amplified by means of a resonant amplifier (modified Knight 93-360) to a suitable level for the direct operation of a low-power servomotor (Bodine Type KCI-22, 17 r.p.m.). The servomotor drives the main slide-wire in the proper direction to reduce the photocell error voltage to zero. At this point the linear dial at-

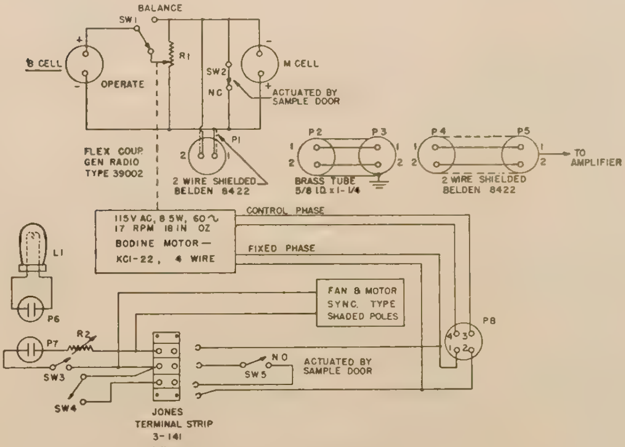
BALANCE
SW1
R1
B CELL
OPERATE
SW2
NC
M CELL
ACTUATED BY SAMPLE DOOR
P1
FLEX COUP. GEN RADIO TYPE 39002
2 WIRE SHIELDED BELDEN 8422
P2
P3
BRASS TUBE 5/8 I.D. x 1-1/4
P4
P5
2 WIRE SHIELDED BELDEN 8422
TO AMPLIFIER
115V AC, 8.5W, 60~ 17 RPM 18 IN OZ
BODINE MOTOR — KCI-22, 4 WIRE
CONTROL PHASE
FIXED PHASE
L1
FAN & MOTOR SYNC. TYPE SHADED POLES
P6
P7
R2
P8
SW3
SW4
NO
SW5
ACTUATED BY SAMPLE DOOR
JONES TERMINAL STRIP 3-141

Figure 2. Measuring Circuit

**$L_1$. Radiant projection, 100 watts, 120 volts**
**$P_1$, $P_4$, $P_5$. Amphenol 80-MC2M**
**$P_2$, $P_3$. Amphenol 80-PC24**
**$P_6$. Jones plug, P-302-CCT**
**$P_7$. Jones receptacle S-302-A8**
**$P_8$. Amphenol 77-MCP-4**
**$R_1$. 500-ohm pot. Helipot SG71**
**$R_2$. 75-ohm, 1.15-ampere max., ohmite 0450, Model K, 100 watts**
**$SW_1$. SPDT toggle**
**$SW_2$, $SW_5$. Microswitch**
**$SW_3$, $SW_4$. SPST toggle**

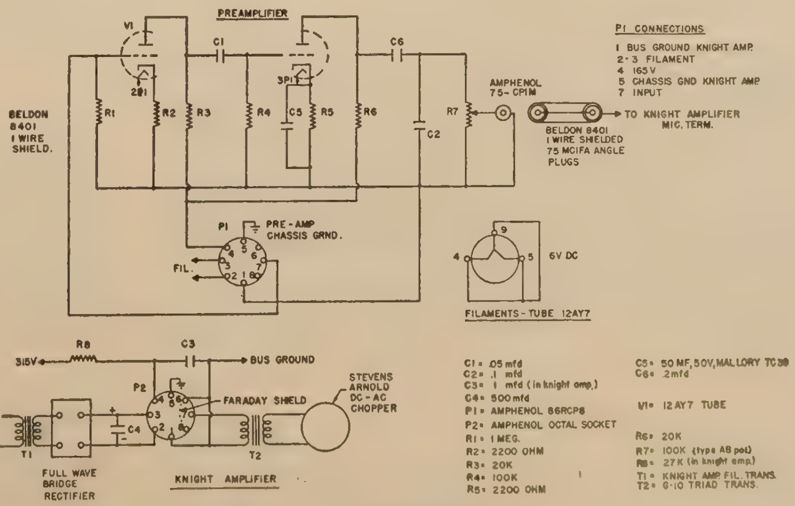
PREAMPLIFIER
V1
C1
C6
3P1
2P1
BELDON 8401 1 WIRE SHIELD.
R1
R2
R3
R4
C5
R5
R6
C2
R7
AMPHENOL 75-CP1M
BELDON 8401 1 WIRE SHIELDED 75 MC1FA ANGLE PLUGS
TO KNIGHT AMPLIFIER MIC. TERM.
P1 CONNECTIONS
1 BUS GROUND KNIGHT AMP.
2-3 FILAMENT
4 165 V
5 CHASSIS GND KNIGHT AMP.
7 INPUT
P1
PRE-AMP CHASSIS GRND.
FIL.
9
4
5
6V DC
FILAMENTS - TUBE 12AY7
R8
315V
C3
BUS GROUND
P2
FARADAY SHIELD
STEVENS ARNOLD DC-AC CHOPPER
C4
T1
T2
FULL WAVE BRIDGE RECTIFIER
KNIGHT AMPLIFIER
C1 = .05 mfd
C2 = .1 mfd
C3 = 1 mfd (in knight amp.)
C4 = 500 mfd
P1 = AMPHENOL 86RCP8
P2 = AMPHENOL OCTAL SOCKET
R1 = 1 MEG.
R2 = 2200 OHM
R3 = 20K
R4 = 100K
R5 = 2200 OHM
C5 = 50 MF, 50V, MALLORY TC38
C6 = .2 mfd
V1 = 12AY7 TUBE
R6 = 20K
R7 = 100K (type AB pot)
R8 = 27K (in knight amp.)
T1 = KNIGHT AMP. FIL. TRANS.
T2 = G-10 TRIAD TRANS.

Figure 3. Preamplifier Circuit

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ent address, Chesapeake Bay Institute, The opkins University, Annapolis, Md.

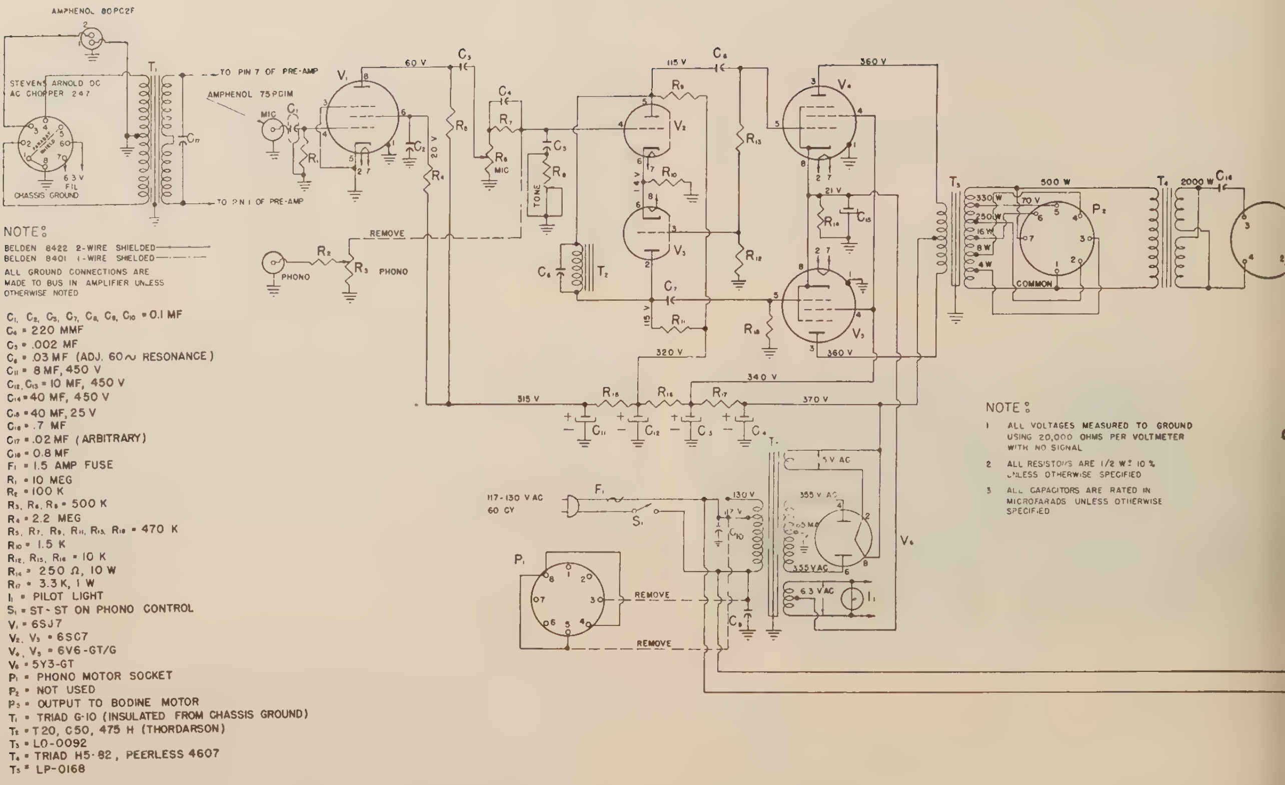
AMPHENOL 80PC2F
STEVENS ARNOLD DC AC CHOPPER 247
FARADAY SHIELD
6.3 V FIL
CHASSIS GROUND
TO PIN 7 OF PRE-AMP
TO PIN 1 OF PRE-AMP
AMPHENOL 75PCIM
MIC
PHONO
REMOVE
TONE
60 V
115 V
360 V
320 V
340 V
370 V
315 V
21 V
500 W
2000 W
COMMON
117-130 V AC 60 CY
5 V AC
355 V AC
6.3 V AC
NOTE:
BELDEN 8422 2-WIRE SHIELDED
BELDEN 8401 1-WIRE SHIELDED
ALL GROUND CONNECTIONS ARE MADE TO BUS IN AMPLIFIER UNLESS OTHERWISE NOTED
C₁, C₂, C₃, C₇, C₈, C₉, C₁₀ = 0.1 MF
C₄ = 220 MMF
C₅ = .002 MF
C₆ = .03 MF (ADJ. 60~ RESONANCE)
C₁₁ = 8 MF, 450 V
C₁₂, C₁₃ = 10 MF, 450 V
C₁₄ = 40 MF, 450 V
C₁₅ = 40 MF, 25 V
C₁₆ = .7 MF
C₁₇ = .02 MF (ARBITRARY)
C₁₈ = 0.8 MF
F₁ = 1.5 AMP FUSE
R₁ = 10 MEG
R₂ = 100 K
R₃, R₆, R₈ = 500 K
R₄ = 2.2 MEG
R₅, R₇, R₉, R₁₁, R₁₃, R₁₈ = 470 K
R₁₀ = 1.5 K
R₁₂, R₁₅, R₁₆ = 10 K
R₁₄ = 250 Ω, 10 W
R₁₇ = 3.3 K, 1 W
I₁ = PILOT LIGHT
S₁ = ST-ST ON PHONO CONTROL
V₁ = 6SJ7
V₂, V₃ = 6SC7
V₄, V₅ = 6V6-GT/G
V₆ = 5Y3-GT
P₁ = PHONO MOTOR SOCKET
P₂ = NOT USED
P₃ = OUTPUT TO BODINE MOTOR
T₁ = TRIAD G-10 (INSULATED FROM CHASSIS GROUND)
T₂ = T20, C50, 475 H (THORDARSON)
T₃ = LO-0092
T₄ = TRIAD HS-82, PEERLESS 4607
T₅ = LP-0168
NOTE:
1 ALL VOLTAGES MEASURED TO GROUND USING 20,000 OHMS PER VOLTMETER WITH NO SIGNAL
2 ALL RESISTORS ARE 1/2 W ± 10 % UNLESS OTHERWISE SPECIFIED
3 ALL CAPACITORS ARE RATED IN MICROFARADS UNLESS OTHERWISE SPECIFIED

Figure 4. Servoamplifier Circuit

tached to the slide wire reads percentage transmittancy directly (by means of a logarithmic dial, absorbancy can be read directly) (Figures 1 to 4).

Essentially monochromatic light is obtained by use of interference-type filters peaked at the desired wave length. Response characteristics of the instrument are controlled by the spectral response of the photocells and by the amount of energy passed by the filter. It is possible to adjust the sensitivity by varying the intensity of the light source and by adjusting the amplifier gain. A preamplifier was added to the circuit, so that high sensitivity is available under most working conditions.

In order to prolong the life of the light source and to prevent fatigue of the photocells, two microswitches are operated by the lid to the absorption cell compartment. When the lid is opened, one switch turns off the light and the other shorts together the two photocells.

During the design of the filter photometer, the following details were found to be of importance.

It is very important to use a working slide wire having very low noise characteristics (less than 5$\mu$v.). For this purpose the Helipot SG-71 500-ohm potentiometer was found satisfactory.

The instrument is sensitive to voltage fluctuations of ±2% or greater. For shipboard installations, Sorensen voltage regulators have been satisfactory.

If the amplifier and photometer are to be used at sea, it is important to install about 20 watts of heater resistors, which should be continuously energized. The heater resistors should be large enough to operate at a low surface temperature (such as a 50-watt resistor actually dissipating 10 watts).

Erratic sensitivity in early instruments was found to be due to inadequate bearings in the Bodine servomotor. When these bearings were replaced with precision bearings, this trouble was eliminated.

## METHOD OF OPERATION

Although the filter photometer may be balanced for 100% transmittance against a cell filled with solvent, customarily it is balanced against an air path. Absorbancy of the cell itself is determined by appropriate cell checks and reagent blank determ tions. This obviates the need for matched cells and reduces number of cells required. Handling of absorption cells, and h breakage at sea, is also reduced.

In making measurements, the instrument is first balanced 100% transmittance, by closing the cell compartment lid throwing switch $SW_1$ to the balance position, thus using the resistance of the slide wire. The balancing photocell is rotated manually until electrical unbalance is eliminated. this point the motor, and hence the dial attached to the wire, stops rotation. The cell containing the sample is placed in the cell compartment, switch $SW_1$ is thrown to measuring position, and the compartment lid is closed. slide-wire dial then rotates until balance is effected. Percen transmittancy is read directly from the dial.

If the power source is sufficiently stable, the initial balan need only occasionally be carried out. Adjustments of source intensity and amplifier gain affect the balance point should be made prior to initial balancing.

## PRECISION OF MEASUREMENTS

In order to establish the precision of measurement of percen transmittancy of the automatic servo-operated filter photom a series of measurements was made of the transmittancy of a shade AKLO filter (Color Spec. No. 1-58, Corning Glass Wo This filter has a fairly flat response in the vicinity of 700 m approximate spectral transmittance at 700 m$\mu$ being 0.35 Baird Associates interference filter peaked at 696 m$\mu$ was us render the incident light essentially monochromatic. A ser 78 readings gave the following results:

| | Average | Std. Dev. | Ra |
|---|---|---|---|
| Percentage transmittancy | 46.56 | 0.09 | 46.4- |
| Absorbancy | 0.332 | 0.0008 | 0.333- |

Contribution from Scripps Institution of Oceanography, New Serie 630. This work was supported by the Marine Research Committee, D ment of Natural Resources, State of California.

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631

ARTHUR, ROBERT S. Calculation of refraction factor along a wave ray. Bull. Beach Eros. Bd., Wash., vol. 7, no. 3, pp. 1-12, 1953. (Unavailable for exchange.)

Reprinted from The Review of Scientific Instruments, Vol. 24, No. 5, 360–361, May, 1953
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# A Thermistor Bridge Correlator*†

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A circuit is described for the measurement of a correlation coefficient between two continuous signals. The method depends on an accurate mean square element which is obtained through the $i^2r$ heating of a thermistor. Relatively simple circuit features give accuracy to about 1 percent, even though the resistance of the thermistor varies by about 25 percent between zero and full input.

ORRELATION methods of dealing with power spectra and coherence of complex signals are re- ving considerable current attention. It may be of erest, therefore, to describe a correlator circuit eloped and found useful in this laboratory. Satis- tory accuracy (about 1 percent) has been obtained ough the use of thermistors as square law elements. he correlation coefficient $\rho$ of two signal voltages and $b(t)$ may be expressed as follows:

$$\rho=\langle ab\rangle_{\text{Av}}/[\langle a^2\rangle_{\text{Av}}\langle b^2\rangle_{\text{Av}}]^{\frac{1}{2}}$$

$$\cong\langle ab\rangle_{\text{Av}}/\tfrac{1}{2}[\langle a^2\rangle_{\text{Av}}+\langle b^2\rangle_{\text{Av}}]$$

$$=\frac{\langle(a+b)^2\rangle_{\text{Av}}-\langle(a-b)^2\rangle_{\text{Av}}}{\langle(a+b)^2\rangle_{\text{Av}}+\langle(a-b)^2\rangle_{\text{Av}}}. \qquad (1)$$

angular brackets denote a time average, and it is posed that $\langle a^2\rangle_{\text{Av}}$ and $\langle b^2\rangle_{\text{Av}}$ are roughly equal, so that ir arithmetic mean is closely equal to the geometric. correlation coefficient $\rho$ then depends, according Eq. (1), on the mean square values of the two quan- es $(a+b)$ and $(a-b)$.

he indicated calculations are performed by the uit of Fig. 1. The signals $a$ and $b$ are combined in a ing network to provide sum and difference signals $-b)$, and $(a-b)$. The sum and difference signals er individual driver amplifiers whose outputs are pled to the thermistor bridge as shown in Fig. 1. gain of each driver amplifier is controlled by rent feedback obtained from the small resistors $r$; in ition to linearizing the amplifiers, this feedback in- ses the output impedance of the amplifiers to the nt where their shunting effect on the thermistor lge circuit is negligible. Under these conditions, each mistor $(t)$ may be considered to be driven by a erator whose impedance is that of the series resistor he value of $R$ is chosen equal to the mid-range value thereby matching the impedance of $t$ to within 2.5 percent. As a consequence of these circuit con- rations, the power dissipated in the thermistor is portional to the square of the amplifier input voltage in an error of ±0.2 percent arising from a change 5 percent in the thermistor impedance.

The thermistors are mounted in close-fitting mercury-filled wells constructed of nickel and press-fitted into a large dural block, whose temperature is controlled by a thyratron circuit and a small heater. The design is intended to provide conduction cooling, with minimum convection in the mercury. Application of audiopower to a thermistor gives a temperature rise which is reproducible and shows a simple exponential decay with time constant of about $\frac{1}{3}$ sec.

These temperature changes are measured through the resulting resistance changes in a dc circuit containing further smoothing filters and meters $M_2$ and $M_1$ which read sum and difference of the two thermistor outputs. It should be noted that while the resistance of $t$ is not a linear function of its temperature, neither is the dc potential across it a linear function of its resistance; it is a further consequence of the approximate equality of $R$ and $t$ that these two nonlinearities cancel in first approximation, so that the final output voltage is quite

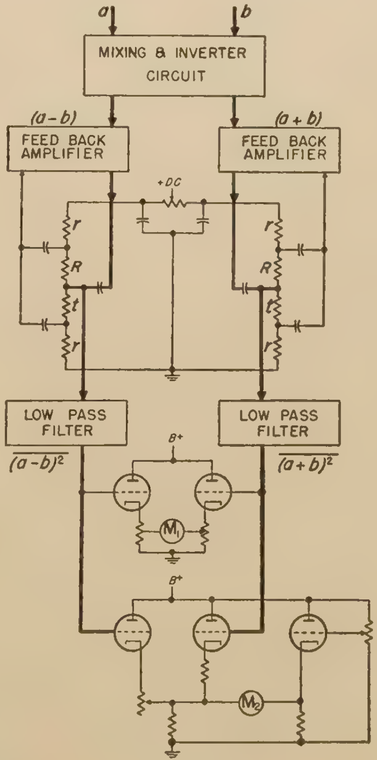

Fig. 1. Diagram of correlator circuit.

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closely linear in the temperature rise of the thermistor, hence also in the mean square of the input signal. An empirical expression for the resistance of the thermistor may be written

$$-\Delta t/t_0 = 1-\exp(-\alpha T)\cong\alpha T-\tfrac{1}{2}(\alpha T)^2+\cdots,$$

giving the relative resistance change of the thermistor in terms of a temperature rise $T$ and a coefficient $\alpha$ which is about 4 percent per °C for the thermistors used. The resulting dc potential change $e$ across the thermistor, relative to total bridge voltage $E$, is then (assuming $R\cong t$)

$$\begin{aligned} e/E &= \tfrac{1}{4}(\Delta t/t_0)-\tfrac{1}{8}(\Delta t/t_0)^2+\cdots \\ &= -\tfrac{1}{4}(\alpha T)+\cdots, \end{aligned} \qquad (2)$$

with the largest omitted term on the right of Eq. (2) of third degree in $(\alpha T)$. Experimentally it was found that $e$ was proportional to the square of the amplifier input potential (and presumably to $T$) to within 1 percent for $(\alpha T)<0.35$.

Thus the two thermistors in Fig. 1 generate signals proportional, respectively, to $\langle(a+b)^2\rangle_{\text{Av}}$ and $\langle(a-b)\rangle^2_{\text{Av}}$. The meters $M_2$ and $M_1$ read the sum and difference of those quantities. In practice $M_2$ is always brought to a fixed normal reading, and $M_1$ is calibrated to read correlation coefficients directly on a linear scale, in accord with Eq. (1).

The circuit as built uses Western Electric Type 14-A
thermistors having a no-signal resistance of 23
ohms at the block temperature (about 60°C).
20 000 ohms and $r$ is 150 ohms. The amplifiers cove
frequency range 50 cps to 10 kc, corresponding to
of a magnetic-tape delay device from which inputs
usually obtained. The maximum undistorted amp
output is about 100 volts rms, while the level c
sponding to the chosen normal reading of $M_2$ is ei
30 volts rms from one amplifier ($a$ and $b$ highly c
lated) or 21 volts rms from each of the two ampli
($a$ and $b$ uncorrelated). The thermistor output be
to depart from square-law only for inputs above
volts rms. Below this power level, the rms deviat
from square law are within 1 percent of full-scale out

The full-scale normal output of the bridge is 1.5 v
to $M_1$, and 0.75 volt to $M_2$. Zero drift has been sa
factorily controlled (within 1 percent of full scale
10 minutes, and 4 percent over 8 hours) by good reg
tion of plate and heater power, and by careful, tho
not elaborate, temperature control of the thermistor

The final filters are required to give steady out
for periods of input signal repetition up to 10 sec a
subject to this condition, are designed to have minim
response time. This proved to be about 2.5 repeti
periods, with a 2 percent overshoot tolerated.

An over-all trial of the correlator, using two sinuso
inputs of known phase difference (ranging from 1
180°) gave correlation coefficients correct to 0.01
1 percent of full scale).

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# he Systematics of Vertebrate Larvae

GRACE L. ORTON

HE interpretation of the larval characteristics of the fishes and amphib- in terms of systematics and evolu- presents many challenging problems. many years, studies on early develop- tal stages were guided by the idea larval characters have an ancestral, pitulative significance, or by the be- that they are secondary adaptations little or no evolutionary importance. her theory is adequate from the stand- t of systematics, and together they e somewhat hampered effective use of al data by taxonomists. A third and e significant concept, based on princi- formulated by Von Baer in the 1800s, gained prominence in recent years ugh the work of de Beer and others. emphasizes comparative studies on valent growth stages of different spe- and provides a much sounder basis nterpreting developmental character- s in terms of systematics and evolu- .

ie larval stage may serve different ogical functions in different animals. uitably adapted larva may enable a ies to succeed in a region that might rwise be closed to it—a conspicuous or in the distribution of many frogs. A gic larva may be the major dispersal e in many marine fishes having slug- or strongly territorial adults, parallel- a well-known life-history pattern in invertebrates. It is often suggested inadequate provision for embryonic ition is the primary factor governing occurrence of a larval stage. Whatever "reason" for its establishment in the geny may be, the larva is subject to operation of genetic evolutionary pro- es, like any other developmental stage, e all growth stages of the individual under the control of a single genetic em.

The same basic procedures of systematics are applied to both larval and adult stages. These procedures include the analysis of variation and the study of differences and of resemblances between species and groups; and the interpretation of the basic data in terms of the primary trends of phylogeny and of secondary phenomena of adaptive radiation, convergence, "rectilinear" trends, and other patterns of evolution, at all systematic levels.

## *Larval Types in Fishes and Amphibians*

The types of larvae that characterize different groups of fishes and amphibians differ widely in their basic characteristics, in the secondary specializations they may undergo, and in the nature of their metamorphosis.

The extant amphibians, comprising about 2500 forms, are classified in three orders (Fig. 1). In the salamanders (order Caudata) and caecilians (order Apoda) the larva is of simple structure, and differs from the adult chiefly in the gill-arch system; other larval characters are usually relatively minor and inconspicuous. In the frogs (order Salientia), larva and adult differ profoundly in many conspicuous characters, and there is a complex metamorphosis. The ecological and physiological aspects of transformation from aquatic larva to terrestrial adult in the amphibians have attracted wide attention. The emphasis on metamorphosis as an adaptive adjustment that is uniformly characteristic of the group has probably tended to divert attention from the extensive and complex differences between kinds of larvae.

In number of extant forms, fishes outnumber amphibians by perhaps 10 to 1. A very wide range of different evolutionary stocks is usually included under the

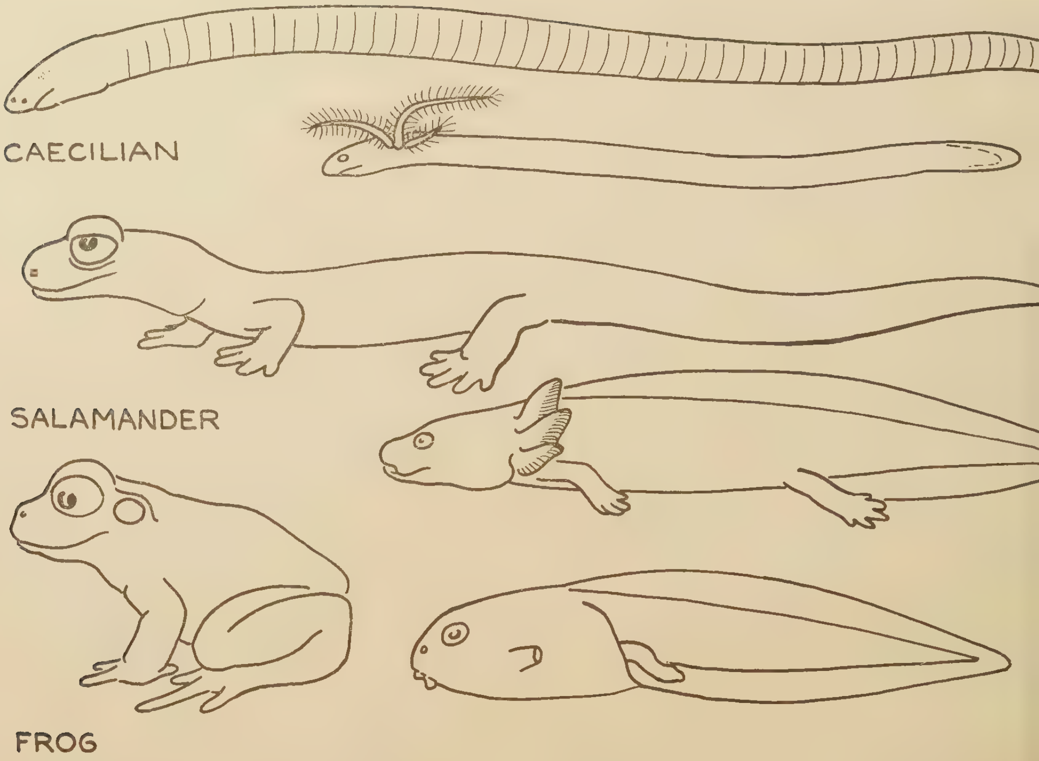


FIG. 1. Diagrams of adult and larval body form in the three orders of living amphibian

general category of fishes—the agnathous groups, the elasmobranchs and related lines, the primitive bony fishes, including the ancestral stock of the amphibians, and the complex and diversified teleost lines. These widely divergent groups show important differences in developmental characteristics that warrant more extensive taxonomic study and interpretation.

Larval characters and their metamorphic changes present somewhat different problems in fishes and in amphibians. Fishes lack the spectacular ecological transition from water to land. Their gill apparatus and other aquatic equipment are retained throughout life, and their larval characters and metamorphic changes are usually more subtle than in the amphibians. But many fishes, particularly in the sea, do undergo a very abrupt ecological and morphological transformation from a pelagic larva to a bottom- or crevice-inhabiting adult.

There are various types of larval char ters in fishes. External gills develop in young of certain lungfishes and a other, chiefly primitive, groups. Adhes mechanisms are found in some ne hatched larvae, especially of fresh-wa species. Many pelagic marine larvae velop some type of flotational mechani (Fig. 2). These modifications include pertrophied fins or finrays (*Lophius,* many others), long spines on the b (Molidae), "ballooning" of the skin (ce tioids, some scorpaenids, etc.), or gel nous dilution of the muscular tissue ( tocephalus larvae of eels and clupeoi Many teleosts are characterized more delay in development of adult form t by special larval structures. But e these species commonly have a defi and more or less prolonged larval st (Fig. 3), characterized by distinctive ea phases in the development of morpholo cal structures and pigmentation.

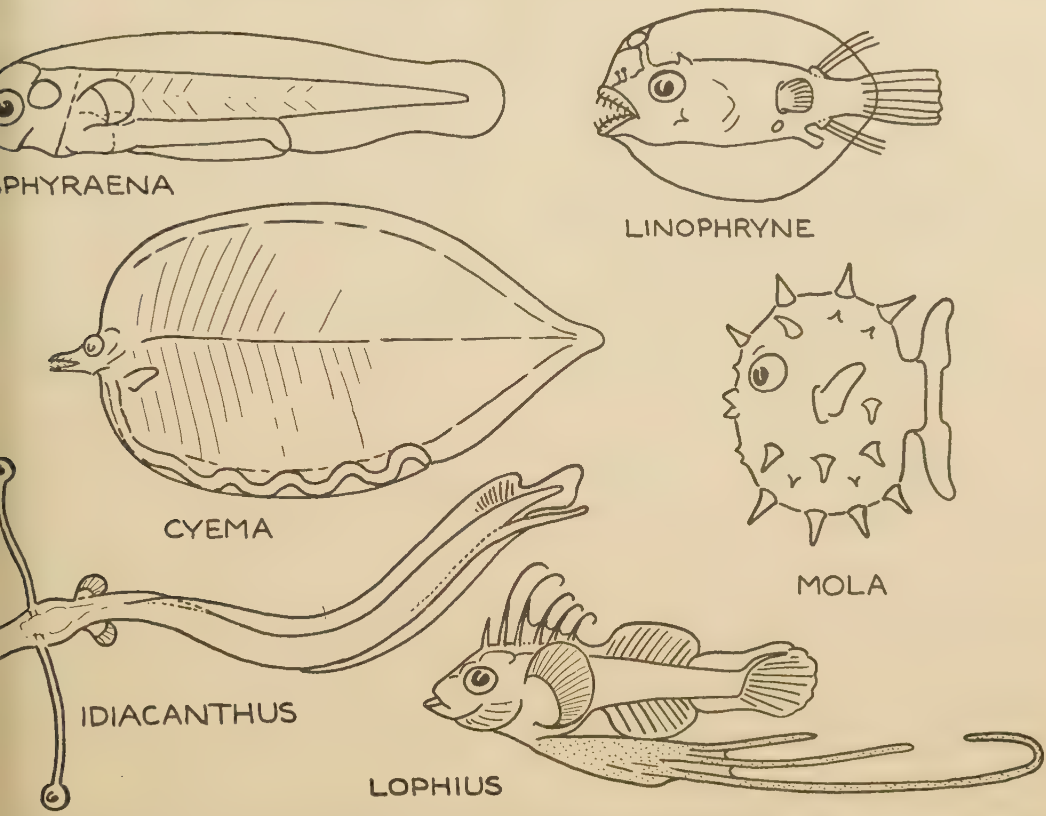


FIG. 2. Five larval fishes with specialized flotational mechanisms, and a generalized larva phyraena, barracuda) for comparison.

Specialized types of larval fishes are metimes designated by special names, ., the ammocetes larva of lampreys and e leptocephalus larva of eels and cluoid fishes. Most of these larval names e carry-overs from the time when such ms were thought to be distinct taxomic entities.

*Specialized Patterns of Development*

The addition of a free-living larval stage the life cycle has led to many spelized types of development, including oteny and secondary direct development. Although these two have opposite sults, it is convenient to discuss them gether, since the effect in each case is e more or less complete elimination of developmental stage from the life cycle. oteny eliminates the former adult stage, and direct development disposes of the larva.

Neotenic animals mature reproductively while they retain some or all of the larval characters. In the salamanders, larval characters are relatively simple, and transformation involves few changes or functional interruptions that critically endanger the immediate survival of the individual. Transitional stages are not necessarily at a serious disadvantage, and indeed the neotenic species differ widely in the degree to which they complete the change from larva to adult. Furthermore, some species are neotenic only under certain ecological or physiological conditions. Neoteny is sufficiently widespread in salamanders to introduce an important complication in taxonomy. In some families all or most species transform completely, and these families are defined on the basis

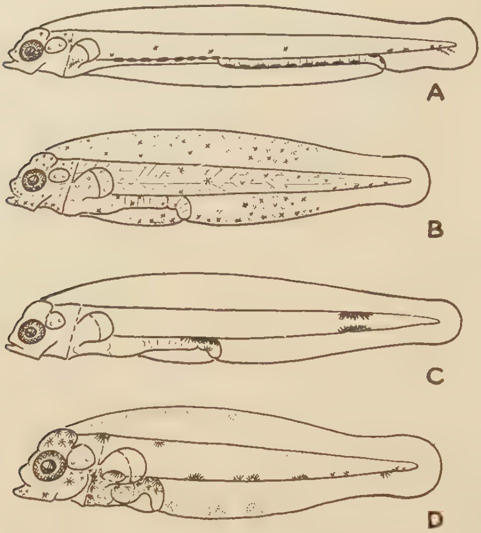


FIG. 3. Larvae of some Pacific Coast fishes showing variation in proportions and in pigmentation, characters used in the identification of larval fishes. *A,* Pacific sardine, *Sardinops caerulea,* Clupeidae; *B,* California halibut, *Paralichthys californicus,* Bothidae; *C,* Señorita, *Oxyjulis californica,* Labridae; *D,* California bonito, *Sarda lineolata,* Cybiidae.

of standard adult characters. But the several families that contain only neotenic species are necessarily defined on the basis of larval or transitional characters. When only a few such forms were known, neotenic salamanders were widely thought to be more primitive, in a recapitulative sense, than forms that undergo a normal metamorphosis. Newer understanding of the role of developmental characteristics in evolution and of the independent occurrence of neoteny in unrelated stocks has helped to clarify the classification of the main groups of salamanders.

In the frogs, metamorphosis is a critical period for the survival of the individual, for the differences between larva and adult are extreme. The changes include drastic shortening of the digestive tract and reorganization of the entire jaw region, as well as the more obvious loss of the gills and tail. Rapid completion of this vulnerable period is advantageous both to the individual and to the species. The change
is probably an "all or none" proces
transitional stages are apparently in
ble of feeding and are poorly adapte
prolonged survival. The apparent abs
of neoteny in the frogs is perhaps as
ated with the extreme complexity of l
anatomy in this group.

Neoteny is apparently rare in f
(fortunately, for the taxonomist), a
probably lacks a strong selective or
petitive advantage in this highly div
fied group. Since larval characters
metamorphic changes are relatively
ple in most fishes, the criteria of neo
in this group are somewhat subjec
Neoteny in fishes, as in the salaman
occurs in various gradations and at
ious taxonomic levels. Certain popula
of *Osmerus mordax* mature when s
and transparent, only slightly if at al
vanced beyond the postlarval stage; s
of the small, transparent, pelagic sp
of gobies are neotenic; the Salangida
neotenic salmonoids; the tiny pe
fishes of the genus *Schindleria* are
tenic postlarvae of uncertain ordina
lationships.

In some groups that normally ha
larval stage, direct development is a
ondary specialization. It is widesprea
amphibians, especially in the frogs, w
it has appeared independently in re
sentatives of nearly every family. In f
that have heavily yolked eggs and te
trial breeding habits, the larva ma
more or less completely lost, in the ec
ical sense, but in all known exam
there is still some anatomical indicati
a larval stage (Fig. 4). In many of t
species the embryo is a very comple
equipped tadpole for a brief period. T
highly modified terrestrial embryos o
have useful taxonomic characters.
unique peltate gills of embryos of
"marsupial" treefrogs (*Gastrotheca*
related genera of the Hylidae) are a
example.

The two main groups of cyclosto
the lampreys and hagfishes, differ gre
not only in anatomy but also in type o
history. The lampreys have small egg

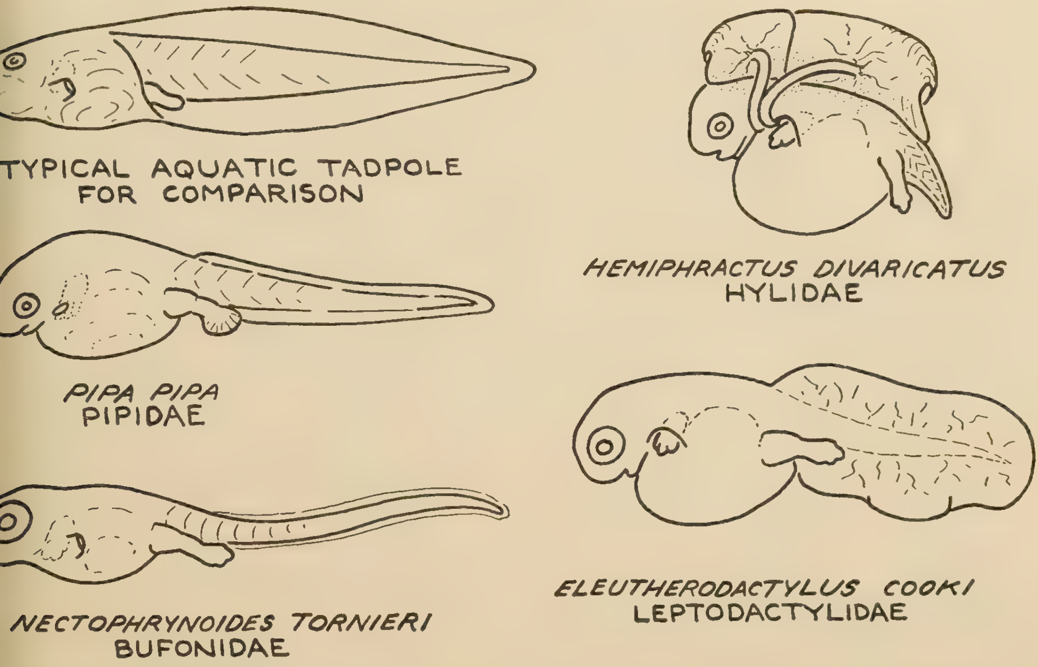

TYPICAL AQUATIC TADPOLE
FOR COMPARISON
HEMIPHRACTUS DIVARICATUS
HYLIDAE
PIPA PIPA
PIPIDAE
ELEUTHERODACTYLUS COOKI
LEPTODACTYLIDAE
NECTOPHRYNOIDES TORNIERI
BUFONIDAE

FIG. 4. Larval structures in embryos of some species of frogs that lack a free-living larval
ige. Peltate gills of *Hemiphractus* form thin sheets completely enveloping embryo, but are
re shown folded back to reveal gill stalks.

rval stage, and metamorphosis; the hag-
hes have large eggs and direct develop-
ent. With a few poorly known excep-
ons, the elasmobranch fishes have heav-
yolked eggs or some provision for uter-
e nutrition, and the newborn young are
latively large and closely resemble the
ults. Among the teleost fishes there is a
mplicated maze of developmental pat-
rns that are greatly in need of taxo-
mic study. Most species have small yolk
serves and hatch in an embryonic condi-
n (Fig. 5, upper two larvae), as do most
phibians. Other fishes have a larger
lk supply, and a greater amount of de-
lopment is completed before hatching
'ig. 5, lower two larvae). The eyes and
ws may be functional and the pectoral
s present (silversides, Atherinidae);
en the caudal fin and the pelvic buds
ay be present (flyingfishes, Exocoeti-
e). In some groups, notably the sal-
nids, not only is development far ad-
nced at hatching, but the yolk reserve
very large and during its gradual ab-

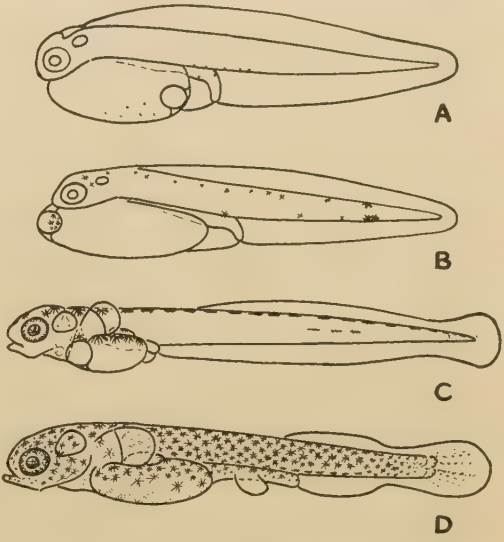


FIG. 5. Differences in morphological characters, pigmentation, and yolk reserves in the newly hatched larvae of some California marine fishes. *A*, Opaleye, *Girella nigricans*, Girellidae; *B*, Señorita, *Oxyjulis californica*, Labridae; *C*, Grunion, *Leuresthes tenuis*, Atherinidae; *D*, California flyingfish, *Cypselurus californicus*, Exocoetidae.

sorption development is carried forward to the juvenile stage. This specialized type of larva is commonly termed an alevin. Many teleosts, of widely divergent relationships, are live-bearing, and their developmental patterns show very useful taxonomic characters. For example, the structure of the trophotaeniae (nutritive rectal processes of the embryo) is now used as a major basis for the classification of the cyprinodont family Goodeidae (Turner, 1937; Hubbs and Turner, 1939), displacing tooth structure, which is subject to much convergence and had led to an erroneous classification.

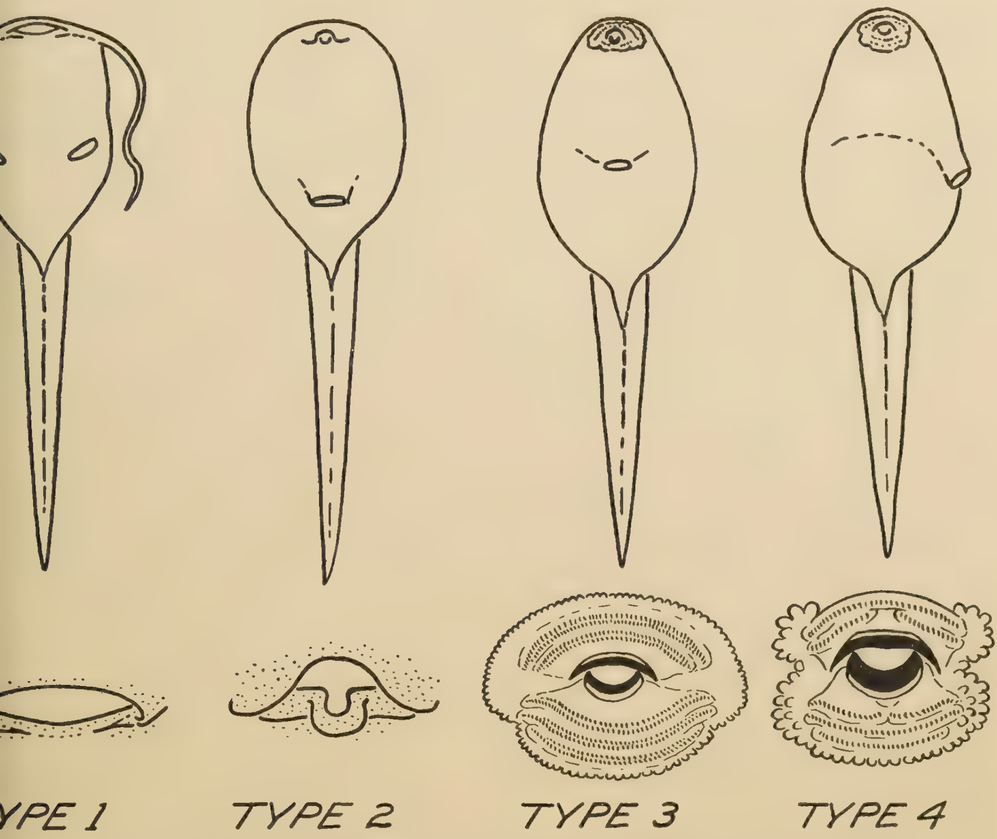
### *Larval Characters As Indicators of Relationship*

Basic anatomical characteristics that are shared by larva and adult (e.g., number of vertebrae) can be expected to follow closely co-ordinated evolutionary trends, for in general a major change in this type of character registers in both stages. But characters that are expressed in only one stage (e.g., horny beaks of tadpoles) may undergo evolutionary modifications that appear only in that stage. In such characters, larva and adult may undergo extensive independent evolution. Larvae can be expected to combine stable characters that vary in close accordance with the main categories of adult classification, with more plastic characters that undergo independent secondary modifications. The secondary trends may be so conspicuous and complex as to mask the more fundamental changes.

Frog tadpoles are notoriously difficult to identify. Their characters are highly specialized, and the seemingly unlimited variation shows little organization on preliminary study. The information now available, however, indicates that the variations and specializations fall into a simple evolutionary pattern of the kind revealed by a study of the adult stages of almost any group of animals, and explainable by the same principles.

Although many of the conspicuous larval characters are excessively vari others are remarkably uniform thro out large taxonomic groups, regardle how specialized the tadpole may b gross appearance and in habits. On basis of very conservative features of internal and external anatomy, all of nearly 600 kinds of tadpoles known t either from original study or from lished data can be grouped into four st types (Fig. 6), each restricted to a fa or a group of families (Orton, ms.). S of the characters are briefly summar here. Three of the types characterize more primitive groups of families based on adult characters), which con relatively few species. The fourth most specialized larval type is numeric dominant, for it characterizes all of more modern, and generally larger, ilies.

The first type characterizes the Pip and Rhinophrynidae, and is consid the most primitive, for it is the simp and most nearly resembles larvae of o vertebrates. The spiracle (an operc structure, not the hyoidean spiracl fishes) is paired, and the right and gill chambers are entirely separate. mouth is a simple slit with narrow la folds. The internal anatomy of the jaw gion is relatively simple; notably, Mec cartilage is long and supports the e lower jaw. The second and third t of tadpoles have a single midventral racle, draining both gill chambers. second type characterizes the Micr lidae, a family of specialized frogs of certain relationships. Their larval cha ters, though not yet adequately un stood, suggest that the family diverge a much more primitive level than is c monly thought. The mouthparts of mi hylids are more complex than in the p type, but are still comparatively sim The basic characters of the mouthp are constant in all microhylids so fa known, though these larvae vary so what in feeding habits and include least one carnivorous form. The t larval type, characterizing the Discogl



G. 6. Ventral views and mouthparts of basic types of tadpoles, to show external char-
of each. Generalized diagrams.

d Ascaphidae, has elaborate mouth-
including wide lips, horny beaks,
bial teeth in transverse rows, all or
f which develop more than one line
th per tooth ridge. The jaw carti-
nd their musculature are complexly
ntiated. In the fourth type the spi-
s single and asymmetrical, on the
de, and drains both gill chambers.
ighly differentiated mouthparts are
r to the third type, but differ in hav-
e labial teeth in single rows (with
xceptions); certain internal charac-
so differ.

use of the well-recognized need for
n against relying too heavily on "nu-
al" characters in classification, em-
has been accorded study of the in-
anatomy of larvae that are highly
ed for unusual habits or ecological
situations. The many variations and peculiar specializations found thus far in such larvae all fall within the framework of the basic types.

Each of the basic types probably represents the condition of the larval stage at a major level of evolution. Neither the larval types nor the groups of adult frogs can be arranged in a linear phylogenetic sequence. Evolution has unquestionably been elaborately radiative in the frogs, as in other animals, and important evolutionary stages have certainly been lost by extinction during the long history of the group.

Within each of the four basic larval types there are well-defined secondary trends that illustrate adaptive radiation and convergence just as clearly as these principles are shown in adult stages.

In patterns of adaptive radiation, the larvae of a taxonomic unit share certain major characters, but in other respects they show divergent modifications that adapt them to different ecological conditions or different ways of life (Fig. 7). No matter how diverse in superficial appearance, however, they retain basic characters indicative of their relationship. The adaptive types include deep-bodied, high-finned nektonic larvae; mountain-stream larvae with an enlarged, flattened snout, huge vacuum-cup mouthparts, and heavy axial musculature; carnivorous forms with hypertrophied beaks and jaw muscles; thin, flattened larvae that live in bromeliads and other restricted arboreal aquatic niches; forms with mouthparts upturned for surface-feeding; and specialized embryos with direct development. There is evidence that adaptive radiation has occurred repeatedly in tadpoles. It is shown at the level of each of the four basic types, within most of the families, and within
some of the larger and better-known g
era (notably *Hyla* and *Rana*).

In convergent evolution, larvae of
ferent taxonomic groups secondarily a
independently develop a common adapt
type. Although they may be strikin
similar in superficial respects, they ret
the basic characters that reveal their
verse origins. Convergent evolution
conspicuously shown in several lar
modifications. For example, mounta
brook larvae that look much alike (Fig.
have evolved independently in at least
of the approximately thirteen families
frogs. Surface-feeding larvae of strikin
similar appearance (Fig. 9) are known
four families. There are examples of
rect development in nearly all families.

Larval fishes also show abundant e
dence of variability, species differenc
and group resemblances. Modifications
larval and other developmental charact
istics have unquestionably followed star
ard patterns of evolution in fishes, as

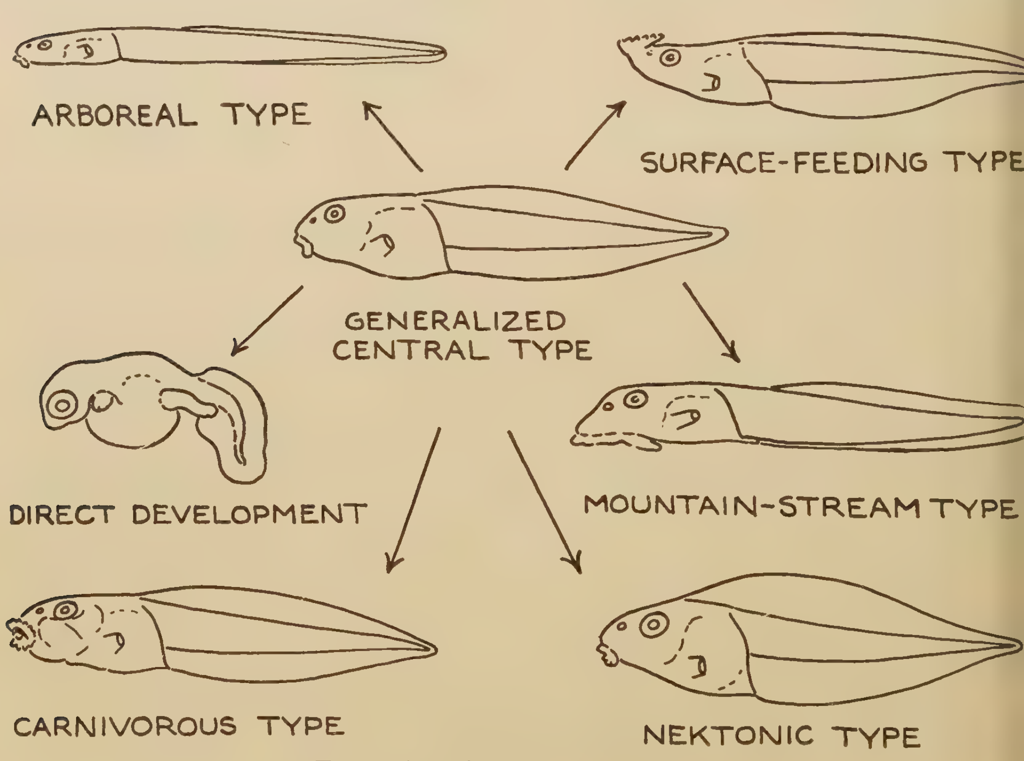


FIG. 7. Adaptive radiation in tadpoles.

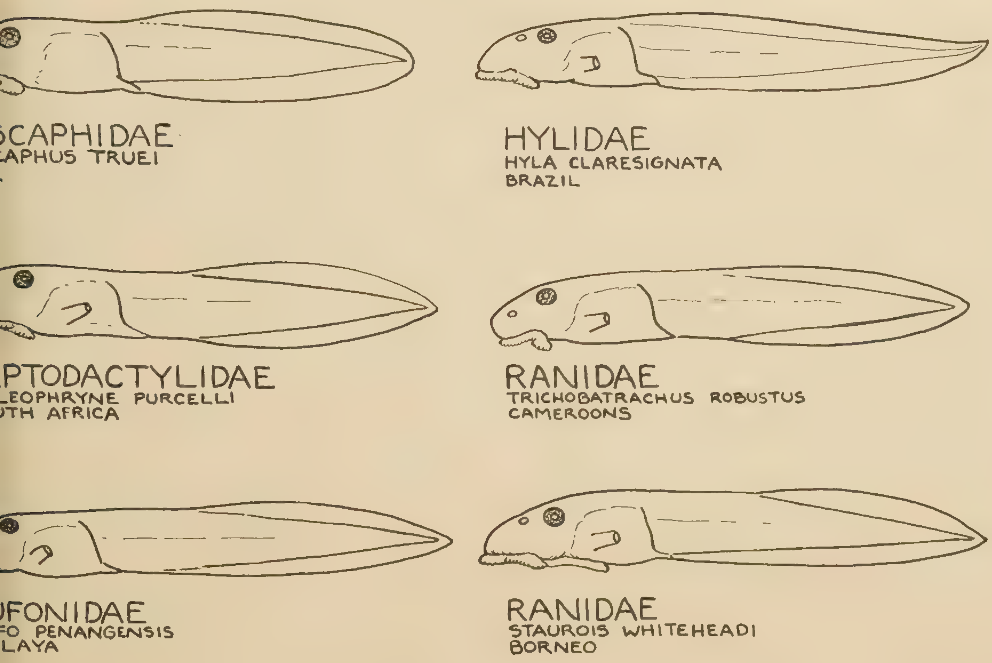


FIG. 8. Convergent evolution in tadpoles of swift streams.

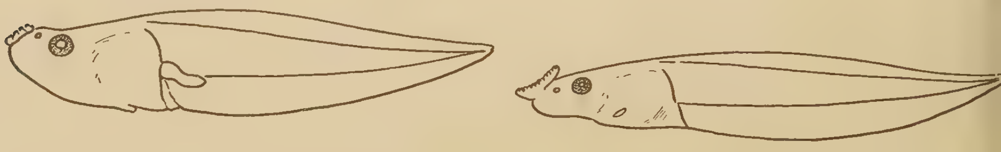
rogs. The problem of working out
interpreting these developmental
cters and trends is one of the fron-
reas of systematic ichthyology.

### *Origin of New Larval Types*

highly complex nature of the frog
le, in contrast to other known types
phibian larvae, presents a problem
val systematics at the ordinal level.
ew known larvae of extinct groups
phibians were very generalized. In
mental form, though of course not
ails, they closely resembled the lar-
of present-day salamanders. The
were long, with simple functional
gement, the body was relatively
and the limbs and girdles were of
proportions. Some fossils show
ce of external gills. The earliest
ibians and the primitive crossop-
an stock from which they arose
bly shared this very generalized
type (or something essentially
r to it), with a minimum of special
structures and a simple metamorphosis. The very long persistence of the simple larva suggests that it has great stability. The present-day lungfishes and salamanders still retain the essential features of this primitive larval type, though they are only remotely and indirectly related to each other.

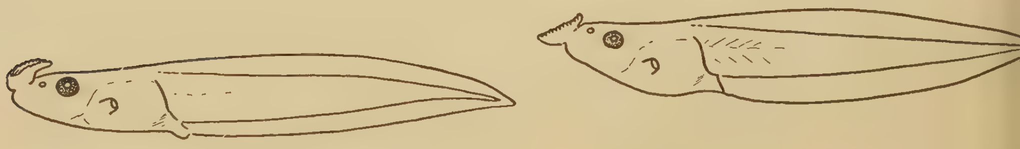
The frog tadpole contrasts sharply with the primitive larva in having a unique combination of distinctive characters. It has a short compact head-body unit, supported by a very short vertebral column, and sharply demarcated from the long tail. The gills and front leg buds are concealed under a closed operculum that retains one or two small excurrent openings. The mouth is small and usually has elaborate external parts; its internal parts are greatly modified and displaced far forward. The intestine is spirally coiled and is usually very long. The highly specialized plan of the frog tadpole is most commonly explained as an adaptation for vegetarian or scavenger habits, in contrast to the carnivorous habits of the adult. Carnivorous habits do, however, characterize a few tadpoles, e.g., those of the *Rana rugulosa* group, but such larvae retain and even further specialize the elaborate characters of their taxonomic group. They show no simplification or basic changes of structural plan such as one might expect if complex mouthparts were directly correlated with adaptation to vegetarian habits. Larval anatomy suggests that vegetarian habits may be a subordinate character, and that a very different primary factor governs the larval type in the frogs. The larval and adult stages differ sharply in most respects, but they do share some of the specializations that place the Salientia well apart from all other known amphibians. Above all, both tadpole and frog have the vertebrae excessively reduced in number (only 6 to 9 presacrals) without a compensating increase in the length of the individual elements. The shortening of the vertebral column is so fundamental that the change almost certainly evolved simultaneously in both stages.

Larva and adult have compensated for reduction in the length of the vertebral column by very different anatomical adjustments (Fig. 10). In the frog the presacral vertebrae occupy only about h
the length of the trunk. The minim
space necessary for the viscera has be
retained by extending the body cav
backward beyond the sacral region. T
posterior extension is supported by th
bones: the two greatly elongated, horiz
tal ilia, and the median urostyle, a cau
element transferred into the body. T
enlarged hind legs and jumping habits
the frog are commonly considered prim
characters, but it is more likely that th
evolved as secondary concomitants of
trend toward excessive shortening of
vertebral column, with its decreased bo
flexibility and loss of the tail as a lo
motor or balancing organ. Space adju
ments in the tadpole have been acco
plished by excessive displacement a
crowding of structures, especially by
forward shift and reorganization of
jaws and gill-arch system, and by d
placement of the forelegs and their c
cealment with the gills under the modif
operculum. The gill-raker system is u
ally large and elaborate. Its actual use
a filter-feeding device in many tadpol
especially pipids and microhylids, sugge



MICROHYLIDAE
MICROHYLA HEYMONSI
CHINA

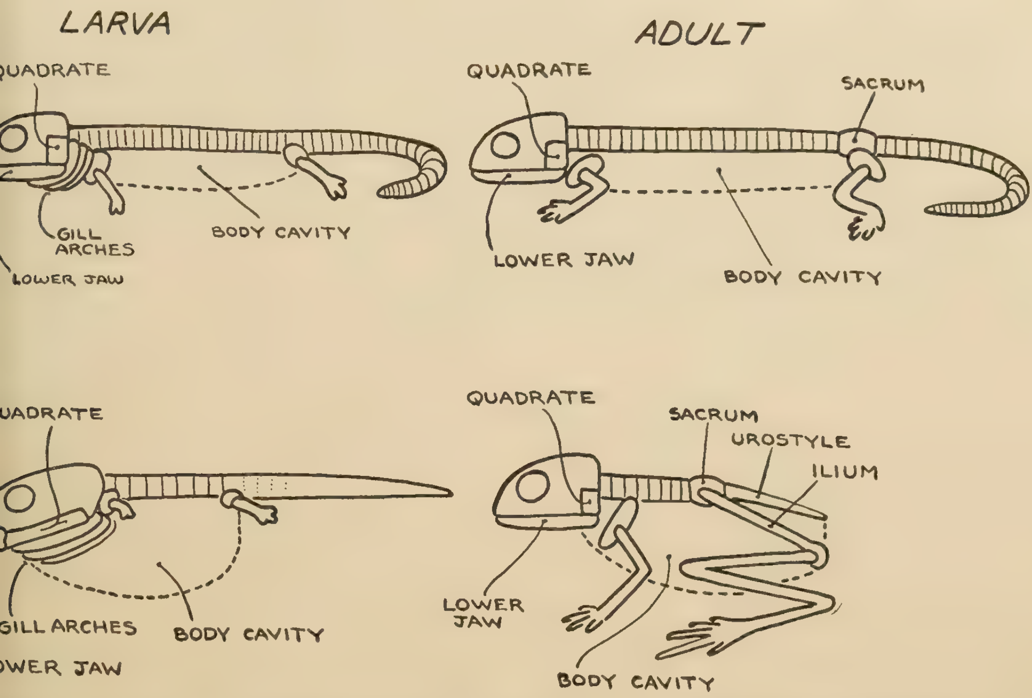
HYLIDAE
PHYLLOMEDUSA GUTTATA
BRAZIL



PELOBATIDAE
MEGOPHRYS MONTANA
JAVA

DENDROBATIDAE
PHYLLOBATES NUBICOLA
PANAMA

FIG. 9. Convergent evolution in surface-feeding tadpoles.



IG. 10. Diagrams to illustrate theory that displacement of structures in frog tadpole, and
tal peculiarities of adult frog, are correlated primarily with phyletic shortening of ver-
l column.

the transitional larval types were
ably plankton-feeders. The more
ern of the extant types have hard
s and grasping labial teeth, and are
commonly herbivorous or feed pri-
ly by chewing on miscellaneous or-
c material. The enlargement of the di-
ve tract to accommodate vegetarian
ts has led to still further crowding of
hortened body cavity.

e known fossil record is of little di-
assistance in tracing the origin and
ition of the frog tadpole. But the
y that the shortening of the verte-
column was the basic factor in the
n of this type of larva can account
all of its chief distinguishing fea-
, and the theory correlates major
ts in both larval and adult evolution.
al and transitional stages of the Tri-
*Protobatrachus* could provide crit-
evidence bearing on the problem,
this very primitive pre-frog is still
n from a single adult specimen.

A trend toward excessive shortening of the vertebral column could lead to rapid extinction if the group lacked sufficient genetic adaptability to permit the evolution of compensating trends. In the frogs, the larval and adult stages, as a co-ordinated unit, succeeded in establishing a very distinctive new anatomical plan, a starting point for an evolutionary radiation that is unusually rich in new taxonomic characters. Although the frogs are now a very old group, the wide distribution and great diversity of specialized types that they still maintain (in both larval and adult stages) mark them as a highly successful evolutionary "accident."

Larval stages may have had an important role in the early history of still higher categories. Several authors, including Garstang, de Beer, Romer, and Gregory, have contributed in various ways to the theory that the entire phylum Chordata may have been established by neoteny from some stock in which the larva was the active stage and possessed the notochord and somites as larval specializations for the support and function of the tail. The adult stage was perhaps sluggish or even sessile. The branchial basket probably functioned originally (in both stages) as a food-filtering apparatus and only later became remodeled for respiratory purposes, after the function of food-snatching had been taken over by jaws.

### *Summary*

A study of the larval stages of fishes and amphibians reveals much important data on their systematics and evolution. Standard methods and theories of modern systematic zoology can be applied directly to the interpretation of larval characteristics. Both larvae and adults show variability, species differences, and group resemblances. In both stages, one can demonstrate primary trends indicating major relationships and secondary trends involving adaptive radiation, convergence, and other evolutionary phenomena. Basic characters of anatomy that are shared by larva and adult (e.g., number of vertebrae) can be expected to follow closely co-ordinated evolutionary trends, for in general a major change in this type of character registers in both stages. But characters that are expressed in only one stage (e.g., horny beaks of tadpoles) undergo evolutionary modifications that appear only in that stage, and in such characters larva and adult can undergo extensive independent evolution. Larvae can be expected to combine conservative characters that vary in close accord with the main categories of adult classification, with more plastic characters that undergo independent secondary modifications. The secondary trends may be so conspicuous and complex as to mask the more fundamental changes.

These general principles are illustrated particularly well in the tadpole stage of the frogs. Indeed, the picture is so clear-cut in this group that it provides an excellent small-scale working model for the study of the vastly more complex larv
problems of the fishes. On the basis c
very conservative features of both inte
nal and external anatomy, known tac
poles fall into four types, each restricte
to a family or a group of families. Eac
of these basic types probably represent
the condition of the larval stage at
major level of evolution. Within each typ
there are well-defined secondary trend
especially of adaptive radiation and co
vergent evolution. There is evidence tha
these trends have evolved repeatedly i
tadpoles. They are shown not only at th
level of each of the four basic types, bu
also within most families and within som
of the larger and better-known gener
Other specialized life-history pattern
such as neoteny and secondary direct de
velopment, have also evolved indepe
dently in unrelated stocks.

The highly complex frog tadpole co
trasts sharply with other known types c
amphibian larvae and with larval fishe
and its interpretation is a major proble
in larval systematics. It is suggested tha
the peculiar combination of characters c
the frog tadpole originated as an adjus
ment to acute internal space limitation
resulting from the extreme shortening c
the vertebral column. The origin of th
tadpole type of larva is thus considered t
be an integral phase of the origin of th
order Salientia.

Larval stages may have had an impo
tant role in the early history of still highe
categories. It is now rather widel
thought that the entire phylum Chorda
may have originated by neoteny fro
some stock in which the notochord an
somites had been larval characters.

### REFERENCES

de Beer, G. R. 1951. Embryos and ancesto
(revised ed.). Oxford Univ. Press.

Gregory, W. K. 1946. The roles of motile la
vae and fixed adults in the origin of th
vertebrates. *Quart. Rev. Biol., 21,* 348–36

Hubbs, C. L., and Turner, C. L. 1939. Studi
of the fishes of the order Cyprinodonte
XVI. A revision of the Goodeidae. *Mis
Publ. Mus. Zool. Univ. Mich.,* No. 42, p
1–80.

ER, A. S. 1946. The early evolution of hes. *Quart. Rev. Biol., 21,* 33–69.

NER, C. L. 1937. The trophotaeniae of the odeidae, a family of viviparous cyprino- nt fishes. *J. Morphol., 61,* 495–523.

is is the second of three papers which prised the Symposium on "Life History ies in Relation to Systematics," sponsored by the Society of Systematic Zoology and the AAAS, St. Louis, December 27, 1952. **GRACE L. ORTON** is a member of the staff of the Scripps Institution of Oceanography, University of California, La Jolla. The material on tadpoles is based largely on the author's Ph.D. thesis, University of Michigan. Contribution from the Scripps Institution of Oceanography, New Series, No. 633.

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# DEVELOPMENT AND MIGRATION OF PIGMENT CELLS IN SOME TELEOST FISHES[1]

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TWENTY-FIVE FIGURES

Experimental studies, especially on amphibians, have convincingly demonstrated that the pigment cells of tetrapod vertebrates normally originate from the neural crest and from there migrate to their definitive positions throughout the body. The literature, methods, and results of these studies have been reviewed comprehensively by DuShane ('43, '48), Rawles ('48), and Twitty ('49). The problem of pigment cell origin in fishes, however, has been very inadequately studied. A brief note by Borcea ('09) on embryos of some marine fishes was apparently the first suggestion that the pigment cells of any vertebrate group originate from an ectodermal source in the neural crest region, but theories of the origin of pigment cells of fishes from mesodermal connective tissue cells, from the germ ring, or from other sources, have long persisted and the recent literature is still somewhat controversial.

In the relatively large embryos of *Belone,* Borcea recognized the color cells before they acquired pigment and traced their migration from a double row along the back (between neural cord and surface ectoderm) downward over various surfaces of the body and to the yolk sac. In *Uranoscopus, Fierasfer (Carapus),* and *Labrax,* which have small pelagic eggs and more rapid embryonic development, he reported that the cells became visibly pigmented while still in the neural region. Experimental work cited by Goodrich ('50) seemed to indicate that the pigment cells, at least those on the yolk sac, may be derived from the germ ring. He concluded: "There does not at present appear to be available critical evidence to demonstrate the origin of fish chromatophores from the neural crest. . . ." Oppenheimer ('50) suggested that under certain experimental conditions the function of pigment cell formation may be taken over by cells normally not involved in this activity, thus perhaps accounting for some of the puzzling experimental results.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 634.

Long-needed experimental evidence that the neural crest is the source of pigment cells in fishes and fish-like chordates has been presented recently by Lopashov ('44) and Newth ('51). Newth's work, on lamprey embryos, is especially significant, for he points out that agreement of lampreys with higher chordates in chromatophore development indicates that the origin of pigment cells from the neural crest is probably a basic developmental feature of very ancient origin, characteristic of the ancestral stock of both the Agnatha and the Gnathostomata.

A relation between pigment cells and neural crest in fishes thus seems to be definitely established, but there is need for much additional study to determine in detail the characteristics of origin and subsequent history of fish chromatophores in order to bring our knowledge of this group into line with the understanding of pigment cell embryology in other vertebrates.

## OBSERVATIONS

Although amphibian embryos and larvae have provided the best evidence for the neural crest theory, they have certain disadvantages for pigment cell study. Amphibian embryos are so opaque in life that very little internal, or even dermal, activity can be observed. Until the chromatophores become pigmented they are difficult to distinguish from connective tissue cells in histological preparations, but by the time they acquire identifying pigment their migration has been completed. It is largely for such reasons that specialized experimental procedures have been needed to trace the source of the cells and their subsequent movements in this group of animals. In striking contrast, living embryos of many teleost fishes are completely transparent, permitting direct observation of internal structural and functional development, including certain aspects of pigment cell history.

In this paper some observations on early pigment development in marine fishes are reported. This work is part of the research on eggs and larvae of marine fishes in progress at Scripps Institution. A major objective is to work out practical identification characters for early stages of large numbers of species, for taxonomic investigations and for assistance in ecological and productivity studies. During embryonic stages and the first few days of larval life many fishes undergo a very rapid and complex development of pigment characters as well as a rapid morphological differentiation, and identification is especially difficult during these stages unless the nature and sequence of the changes are well understood. In order to obtain more complete information on this brief transitional period in both morphological and pigment development, live eggs and larvae are being utilized in addition to preserved specimens. To date, early stages of more than 40 species of California marine fishes have been studied from living material. These forms are very diverse taxonomically, in respect to size and ecology of the eggs, and in developmental characteristics. The observations on early development of pigment characters in these fishes are helping to clarify identifications, and as a by-product they have a bearing on basic pigment cell problems. They confirm and substantially augment Borcea's brief indication that the origin and dispersal of pigment cells from the neural crest region can be traced *in vivo* in some fishes. In many of these species the chromatophores become pigmented so early in their development that much can be learned of their place of origin and their migration and orientation into patterns by merely observing the living specimens at suitable intervals for a period of several days, as Borcea apparently did. In nearly all of the more than 40 marine species that I have studied *in vivo* thus far, there is a clearly evident primary center of pigmentation along the dorsal and/or dorsolateral surfaces of the body and tail (i.e., in the neural crest region), with subsequent migration of the cells elsewhere to various secondary positions. In some species events proceed with an orderly simplicity that is almost unbelievably diagrammatic. The best examples are to be found among species that have small, rapidly-developing pelagic eggs. In these the yolk sac, as well as the body, is usually completely transparent, so there is nothing to impede the view in any dimension. In early stages of many of these fishes one can easily study critical aspects of chromatophore history that can be explored in amphibian embryos only by very indirect means.

In contrast, pigment formation in fishes that have relatively large eggs or slow embryonic development (or both) is commonly delayed until after the cells have undergone more or less extensive migration, as is true in amphibians. Simple observation is, of course, not sufficient to reveal the early history of the chromatophores in these fishes. Furthermore, in demersal eggs with slow development the yolk sac is often densely granular and more or less opaque, interfering somewhat with observation of internal processes, even though the embryo itself may be transparent.

The early development of pigmentation in several marine fishes with small pelagic eggs will be described briefly. The species selected for discussion are arranged to show successively more complex types of larval pattern development, from species in which the area of differentiation and the migration of the pigment cells are visible with the utmost clarity and simplicity to species in which pigment formation is so delayed that neither the place of differentiation nor the migration are definitely visible in living specimens. The developmental rates given are for ordinary room temperature.

The terms melanophore and black pigment cell are here used interchangeably, but light-colored cells are named only by the appropriate color (yellow, brownish-buff, etc.). The exact color characteristics of the latter cells vary widely, and in some species there are progressive differences in cell color in successive embryonic and larval stages. The biochemical studies necessary for precise chromatophore terminology are beyond the scope of this paper.

PACIFIC SARDINE, *Sardinops caerulea* (Family Clupeidae). — In the early stages of the Pacific Sardine pigment cell development and pattern formation follow a very simple, strikingly diagrammatic sequence (figs. 1–5). A brief description of it published elsewhere antedates the present paper (Miller, '52). In the advanced embryo there are two rows of small, inconspicuous, "contracted" melanophores along the dorsolateral surfaces of the body and tail. A few additional melanophores are scattered over the upper surfaces of the head, and there are several in a double row along the lower edge of the very short tail. This pattern persists in the newly hatched larva. During the first day following hatching the melanophores in the dorsolateral rows enlarge and become stellate, and their pigmented processes begin to show some vertical orientation. In day-old larvae these melanophores are unmistakably in the process of migration downward over the lateral surfaces of the somites. They are sprawled about in various amoeboid positions, predominantly with a vertical or oblique orientation. As this stage progresses, the cells begin to reach the lower edges of the somites, where they "contract" into horizontal bars and become oriented lengthwise into two rows along the greatly elongated body cavity. The migration is essentially completed in the two-day larva. The two rows become stabilized along the dorsolateral surface of the body cavity anteriorly, and along its ventrolateral surface posteriorly. A few small melanophores persist on the upper surface of the head, and a few stray cells on the sides of the somites.

The changes observed during formation of the early larval color pattern in the Pacific Sardine are very simple and involve only a moderate number of cells. These larvae, and those of related species, should be excellent material for study of the dynamics of melanophore migration in the living larva through the use of time-lapse motion picture photography and other techniques.

Essentially the same characteristics of larval pattern development can be interpreted from published notes and illustrations of a number of related fishes, and are probably typical of most clupeids with pelagic eggs. The newly hatched larva of the European Sardine, *Sardina* [*Arengus*] *pilchardus,* figured and discussed by McIntosh and Masterman (1897), shows small black cells scattered along the upper and lateral surfaces of the body. The authors noted that on the 4th day "the black chromatophores have encroached upon the ventrolateral region." The eggs and early larvae of another clupeid fish, the Menhaden *(Brevoortia tyrannus),* described and figured by Kuntz and Radcliffe ('17), very closely resemble the corresponding stages of the Pacific Sardine. The embryos were stated to develop small black pigment cells on the dorsal and dorsolateral surfaces, a pattern persisting in the newly hatched larva. The next stage described by Kuntz and Radcliffe was a 4-day larva in which black cells occurred in a series along the gut and were absent from the dorsal surfaces of the larva except near the tail tip. The critical intervening stages that could illustrate a definite migration apparently remain undescribed. Several species of Menhadens are abundant and variously distributed along the Atlantic and Gulf coasts of the United States, and constitute a major fishery resource. Their larval development should be studied more fully, for pigment cell history in these forms may be as amenable to study as it is in the Pacific Sardine.

SHEEPHEAD, *Pimelometopon pulchrum* (Family Labridae). —Larval pattern development in the Sheephead (figs. 6–11) follows a course almost as simple as in the Pacific Sardine, but the migrating cells are somewhat more abundant and less strikingly amoeboid. In the early embryo, shortly after the body axis, eyes, and some of the somites become clearly defined, small, pale-gray pigment cells appear along the dorsolateral surfaces of the body, between the tops of the somites and the neural region, and a few are visible on the yolk sac. In an older embryo, with a well-defined tail (fig. 6), the melanophores are moderate in size and number and are concentrated in two irregular rows along the dorsolateral surfaces of the head, body, and tail. A few additional melanophores occur along the lower edge of the tail somites, in a median line on the posterior surface of the yolk sac, and in a patch covering the upper surface of the oil globule. This pattern persists until after hatching. In the newly hatched larva a few melanophores may have reached the sides and there may be a few on the lower surface of the gut. During the first day there is a transitory stage in which migrating melanophores are very uniformly distributed over the sides of the trunk and tail. In the larva about one day old (fig. 9) a moderate number of melanophores remain on the sides, but many of them have reached the ventrolateral surfaces of the somites, where they are assembling in two rows. The cells that form a pair of short dorsolateral rows along the tip of the tail apparently do not migrate. A few melanophores occur on the head, especially in a circle around each eye, and there are still a few on the oil globule. In a two-day larva migration is essentially completed, and most of the pigment cells are densely crowded into two nearly solid rows along the ventrolateral surfaces of the somites from the pectoral region back nearly to the tail tip.

Señorita, *Oxyjulis californica* (Family Labridae).— In this common California species (figs. 12–16) the development and migration of the melanophores begin essentially as in the fishes discussed above, but later stages of the migration are complicated by aggregation of the cells into several large blotches. The embryonic stages were described and figured by Bolin ('30), and my observations confirm his and add further details on pigmentation. In the early embryo with the tail bud not yet free, melanophores are already visible in a pair of dorsolateral rows between the tops of the somites and the neural region, extending from the hindbrain to near the tail bud. A few are irregularly scattered dorsally. During this stage it can be seen definitely that the melanophores on the oil globule in this species do not originate *in situ*. For a period of a few hours, about a half-dozen or more small melanophores can be observed assembling in an irregular circle on the surface of the yolk sac some distance outward from the oil globule. These cells converge toward the oil globule and move inward, apparently following its enveloping membrane, and aggregate to form the patch of black cells that characteristically covers the upper surface of the oil globule. In the advanced embryos and the newly hatched larva (figs. 12–14) most of the melanophores on the body and tail retain their dorsolateral position, but some have begun moving downward. On the distal third of the tail a few cells on both dorsolateral and ventrolateral surfaces have become variably enlarged to form a vaguely defined dark bar. During the first day after hatching the migratory melanophores move down over the sides and horizontally, and most of them assemble to form three conspicuous and apparently constant blotches: two that lie somewhat posterior to the midtail region (one on the upper and one on the lower edge of the somites), and one above and around the angle of the hindgut. In some individuals several minor aggregations are variously distributed along the tail and the gut. This pattern is well-established in the two-day larva and persists at least through the first 5 days of larval life, with further enlargement of the patches of melanophores on the tail and on the hindgut.

Essentially the same type of larval pattern development characterizes the Cunner *(Tautogolabrus adspersus)*, a common Atlantic labrid. Pigment characters of this species, described and figured by Kuntz and Radcliffe ('17), clearly indicate migration of melanophores from a dorsal center and their aggregation into a few large blotches arranged much as in *Oxyjulis*. Pattern development in larvae of several European labrids is also very similar, judging from published illustrations.

PACIFIC MACKEREL, *Pneumatophorus japonicus diego* (Family Scombridae).— In the early stages of the Pacific Mackerel, pattern development is complicated by the occurrence of both black and yellow cells, and the two types of chromatophores have independent histories (figs. 17–21). The differentiation and migration of the melanophores proceed along the same general lines as in the Sardine and Sheephead described above. The migration was clearly shown, though not described, by Fry ('36) in colored figures of eggs and three successive larval stages. In the early embryo with the tail bud just forming (fig. 17), small grayish pigment cells are distributed over the dorsal and dorsolateral surfaces of the body, as far forward as the hindbrain, and some are scattered over the posteroventral surface of the yolk sac. In a more advanced stage with a short free tail bud, both black and yellow cells are well differentiated. Most of the black cells are crowded into a pair of dorsolateral rows. On the anterior half of the body some are more widely scattered over the dorsal surface and on the sides of the somites, and a large group has reached the upper surface of the oil globule. Yellow cells form a large blotch behind each eye, and are distributed in a broad zone along the posteroventral surface of the body. In the advanced embryo, shortly before hatching (fig. 18), there is still a conspicuous double row of black cells along the dorsolateral surfaces of the body and tail. Yellow cells are distributed chiefly in the large spot behind each eye, a patch over the outer surface of the oil globule, a loosely aggregated zone along the dorsolateral surfaces in midbody region, and a wide dense band around the somites at midtail. During the first day following hatching most of the melanophores move downward from the two dorsolateral rows and take up new positions along the ventrolateral edges of the somites and along the top of the gut. There is little change in the pattern of yellow pigment. In the day-old larva the melanophore migration is essentially completed; the melanophores along the lower edge of the tail are now aligned in an irregular single median row, and those along the top of the body cavity form two rows. The broad yellow band in midtail region is more diffuse; its component cells are more distinctly separate and are now confined largely to dorsal and ventral positions. The other concentrations of yellow pigment cells also appear to be dispersing. In the two-day larva little or no yellow pigment is visible on the tail, and the yellow areas on body surfaces are reduced. In somewhat older larvae new black cells begin to appear along the dorsal surfaces of the head and body.

Early stages of the Atlantic Mackerel, *Scomber scombrus,* appear to differ from those of the Pacific Mackerel in lacking a yellow band on the tail, in having heavier black pigmentation in corresponding stages, and apparently in lacking a clearly visible migration of pigmented cells (Cunningham, 1889, 1891; Holt, 1893). The development of pigment cells in this species should be re-studied from live material, especially to check the last-mentioned characteristic.

CALIFORNIA BONITO, *Sarda lineolata* (Family Cybiidae).—Both black and yellow pigment develop early in this species of Bonito, as in the related Mackerels, but the details of pattern formation differ considerably. Small, light-gray pigment cells are already clearly visible in an early embryonic stage in which Kupffer's vesicle is still present and the caudal end of the embryo has not yet formed a definite tail bud. Most of the pigment cells are distributed along the dorsolateral surfaces and upper sides, and many of them are conspicuously associated with the zone where the tops of the somites meet the neural region; a few are scattered over the upper surfaces of the yolk sac. In a slightly older stage, with a very short free tail bud, the chromatophores are more conspicuous and somewhat more abundant; many along the sides of the body are very amoeboid and are evidently beginning to migrate downward. On the surface of the yolk sac a group of highly amoeboid pigment cells are converging toward the oil globule, and additional cells are scattered over the upper surface of the yolk sac. In the advanced embryo with a long, laterally-displaced tail and well developed finfolds, the melanophores are larger and have more extensive amoeboid processes. Along the body a moderate number remain dorsolateral but many have moved down onto the sides, and along the distal part of the tail most have already reached the lower halves of the somites. Migrating melanophores have assembled on the upper surface of the oil globule, and others are widely scattered over the yolk sac. In this stage small yellow cells are heavily massed in the bases of both the dorsal and ventral finfolds, and a few are scattered along the body and on the yolk sac. In a slightly more advanced embryo some of the yellow cells have moved out into the dorsal finfold and have aggregated in groups near its margin. In the newly hatched larva the downward movement of black pigment cells has progressed further. In the day-old larva the process is virtually completed, for the melanophores are now assembled along the lower edges of the somites and the top of the body cavity. The melanophores are relatively smaller, grayer, and less conspicuous than in the Pacific Mackerel. The aggregations of yellow pigment cells in the dorsal and ventral finfolds of the Bonito enlarge into conspicuous blotches after hatching, and these persist through at least the first five days of larval life.

Diamond Turbot, *Hypsopsetta guttulata* (Family Pleuronectidae).— Early stages of many species of flatfishes are very heavily and rather uniformly pigmented, and the migration of chromatophores is obscured by the abundance of the cells and is difficult to trace by ordinary observation of living specimens. But even in some of these species it is clearly evident that early phases of pigment cell differentiation take place on the dorsal and dorsolateral surfaces of the embryo. For example, in the early embryo of the Diamond Turbot, with Kupffer's vesicle still present and the tail bud not yet free, very small pigment cells are densely sprinkled over the upper surfaces. Heavy concentration of many of the cells along the upper parts of the myocommata suggests that these septa are major migration routes. Superficially, the cells all appear grayish at this stage, but careful light adjustment reveals that most of the more dorsal cells are black and most of those farther downward are dark yellowish-brown (faintly yellow in reflected light). The arrangement is especially diagrammatic on the tail bud. Here the yellowish-brown cells are most abundant horizontally in the zone between the neural keel and the tops of the somites and vertically along the myocommata, and most of the tiny black cells are scattered over the upper surface of the neural keel. A few very small, apparently blackish, pigment cells occur along the extreme upper surface of the yolk sac and along its posterior surface between the tail bud and the oil globule.

In older embryos, with the tail well-defined but not yet displaced laterally, chromatophores are larger, more numerous, and are conspicuously differentiated in color. Black cells heavily dot the upper surfaces and are randomly distributed except on the tail, where they are concentrated in two dorsolateral rows. A few black cells lie on the upper surface of the oil globule. Brownish-buff cells are widely distributed but are most abundant along the ventrolateral surfaces of the somites of trunk and tail, and the dorsolateral surfaces of the latter. Additional brownish-buff cells are sparsely scattered along a narrow ventral zone across the yolk sac from head to tail base, and form a distinctive circle around the oil globule where it adjoins the surface of the yolk sac.

In subsequent stages, both black and brownish-buff cells (the latter becoming yellow) are so abundant and so uniformly distributed that no definite pattern is apparent.

Opaleye, *Girella nigricans* (Family Girellidae).— Pigment cell development and pattern formation in early stages of the Opaleye present a more complicated picture (figs. 22–25), for the embryonic stages appear to be entirely devoid of pigment, and the pattern formation that eventually takes place shows no definite indication of cell migration. In the newly hatched larva there are a few small, very inconspicuous and easily overlooked melanophores along the upper and lower surfaces of the hindgut and on the midventral surface of the somites at the base of the tail. Scattered over the lower surfaces of the yolk sac there are a few non-pigmented but optically-defined cell-like objects that may prove to be undifferentiated pigment cells.

In the day-old larva abundant small melanophores form two irregular rows along the top of the gut and a closely crowded single row along the midventral edge of the tail, and there are a few cells along the midventral edge of the gut. Near the tip of the tail there is a short middorsal row of small black cells; there are also a few cells on the yolk sac, chiefly along its ventral and posteroventral surfaces. In the two-day larva the pattern remains essentially the same, except that the cells have become enlarged and conspicuously dendritic, and probably have begun to aggregate. At the age of three days (fig. 25), there is heavy black pigment along the entire upper surface of the body cavity. The midventral edge of the tail bears a row of about 8 large, highly branched black spots, each probably an aggregate of several melanophores. New black pigment has appeared along the middorsal surface: there is a large, highly branched, toupee-like blotch over the top of the midbrain, a smaller one above the pectoral region, and a variably-spaced series of about 6 or more along the top of the tail. One or two small, inconspicuous black cells have appeared on the midlateral septum along the tail. There are a few additional black patches around the viscera, as is indicated in the figure. In larvae 5 to 7 days old, the pattern remains the same except for the addition of iridescent pigment, presumably guanophores, along the upper surfaces of the body cavity.

The lack of a definitely visible migration of pigment cells in the Opaleye is probably the result of delay in pigment formation until after the cells have reached more or less permanent locations, as is true in amphibians.

ANCHOVIES (Family Engraulidae).— This large, complex family of clupeoid fishes is closely related to the Clupeidae (Sardines, Herrings, Menhadens, etc.). In early stages the species of the two families are very similar in most respects, but they appear to differ consistently in several developmental characters, including time of first appearance of visible pigment. In Anchovies, pigment formation is typically delayed until after migration of the cells has taken place. When they first become visible the melanophores already lie along the gut and on the lower surfaces of the tail somites. This is indicated in published accounts of many kinds of Anchovies, including the Pacific *Engraulis mordax* (Bolin, '36; and personal observations), and the Atlantic *Anchoviella eurystole* (Kuntz and Radcliffe, '17).

## DISCUSSION

The groups of freshwater and brackish water fishes that have been most extensively investigated by embryologists appear to parallel the amphibians in the delay of pigment formation until after the cells have undergone extensive migration. These groups include cyprinid fishes *(Carassius, Brachydanio,* etc.) and cyprinodonts *(Fundulus, Oryzias,* etc.). The almost universal use of these forms as the basis for recent embryological studies on fishes has perhaps indirectly tended to discourage study of developmental problems in other groups of teleosts. For whatever reason, the embryology of marine fishes with small pelagic eggs has received very little study by modern methods, but the simple observations presented here on the early pigment cell history in some of these teleosts suggest that this material has extraordinary utility for certain types of research, and should receive much more extensive study.

The species described above were in part selected to illustrate differences in the stage of pattern development at which the chromatophores become visibly pigmented, since some species are much more suitable than others for studies *in vivo*. If pigment appears before the cells leave the neural crest region the entire course of the migration can be clearly seen (e.g., Pacific Sardine). If pigment development is delayed, migration can be traced readily only in its later stages or not at all (e.g., Opaleye and Anchovies). Furthermore, the critical migratory phases are of brief duration. The conspicuous first wave of migration is accomplished quickly and could easily be overlooked or misunderstood, and indeed it has been largely overlooked even in the extensive descriptive literature. In many of the species studied in the present investigation, this first wave of pigment cell dispersal rapidly establishes a basic pattern of pigment locations and cell aggregations that is then retained throughout a more or less prolonged larval life. The very early larval stages of many species are delicate and easily damaged or lost in collecting gear, hence even the taxonomic literature on larval fishes often describes only larvae that, although very small, have already achieved a relatively fixed color pattern.

The literature on the early development of fishes hatched in the laboratory does contain many descriptive notes and illustrations that indicate primary appearance of pigment on the dorsal or dorsolateral surfaces of the embryo, with subsequent changes in location of the pigment. Many of these references long antedate Borcea's brief note ('09), but the interpretation of pigment development, when attempted at all, was in terms of the prevailing concepts of chromatophore origin from such sources as mesodermal connective tissue cells, or undifferentiated cells in the germ ring. It was clearly recognized by a number of early workers that some sort of migration of pigment cells may take place. For example, Ryder described developmental changes in position and arrangement of pigment cells in the Spanish Mackerel (1882) and Cod (1884), and concluded that these changes can be explained only as the result of actual migration of the cells. Agassiz and Whitman (1885) described and carefully figured successive stages in pigmentation in embryos and larvae of several species of marine fishes, but the text gives no indication that they attached any significance to the consistent development of melanophores in a pair of rows at the "dorsal angles" of the somites in different species, or to the basic similarity in the subsequent changes in arrangement of the cells. They clearly illustrated (their pl. 16, figs. 1–8; labelled *Pleuronectes americanus* but probably representing *Tautogolabrus adspersus)* successive stages in the migration and aggregation of the melanophores from a pair of dorsolateral rows into a few large blotches, chiefly on the tail and on the gut, but the especially clear-cut intermediate step (their pl. 16, fig. 6) was described as a variant specimen. Agassiz indicated that he planned a detailed account of pigment development in fishes, but unfortunately this was apparently never published.

The history of yellow and red pigment cells of various types is somewhat less obvious than the history of the black cells in the species I have studied thus far, but at least nothing has been observed that would discount a neural crest origin for them. Association of brownish-buff cells with the neural crest region in the early embryo of the Diamond Turbot has already been mentioned. These cells become yellow in later stages. In the Tubesnout *(Aulorhynchus flavidus)*, a specialized relative of the Sticklebacks, chrome-yellow pigment cells make their first appearance in the embryo as a pair of rows along the dorsolateral surfaces of the somites of the posterior part of the body and anterior part of the tail. These cells then aggregate into a dense, opaque yellow blotch middorsally on the base of the tail.

In some species, some of the centers of concentration of black and yellow cells coincide when the larval pattern becomes well established, e.g., in some flatfishes of the genus *Citharichthys* (not described here), but in general there is a strong tendency for different types of pigment cells to migrate and aggregate independently, as in the Pacific Mackerel and California Bonito. This condition is probably associated with fundamental biochemical differences in the cells and in the forces to which they respond while in a mobile stage.

Disappearance of yellow pigment in young Mackerel larvae was described above. The fate of the yellow cells is not apparent from these observations, but it is unlikely that they actually disappear. There is conspicuous loss of yellow color after the first few days of larval life in a number of other species, and it seems possible that the cells simply become de-pigmented and are held inactive until a later period of development. In the Kelpfish, *Heterostichus rostratus* (Family Clinidae), advanced embryos and newly hatched larvae have a series of very large, conspicuous, complexly branched yellow patches distributed in a distinctive pattern, in addition to black pigment. After hatching, the yellow spots begin to diminish in size, and in a larva three or 4 days old the only traces of them that can be seen are a few minute, scarcely visible, orange dots. In fishes that have a prolonged transparent and sparingly pigmented larval stage, heavy pigmentation commonly appears very abruptly at metamorphosis. In a comparable situation in salamanders it has been shown experimentally (Twitty and Bodenstein, '39) that the heavy pigmentation developing at metamorphosis is formed by rapid acquisition of pigment in a large number of cells, which had originated and dispersed from the neural crest at an early stage but had remained unpigmented during larval life. The time available for formation and dispersal of pigment cells from the neural crest is quite limited, for the crest is apparently entirely expended in giving rise to its various derivatives (Hörstadius, '50). Thus, the embryo can perhaps be said to "stockpile" its pigment cells during the brief period of availability.

Pelagic eggs of marine teleosts may provide material for definite answers to several other questions on chromatophore development. For example, it is not yet known whether the potentialities of cells derived from the neural crest (to form chromatophores, spinal ganglia, visceral cartilages, or other structures) are already determined before cell migration begins, or whether their ultimate type depends on where migration happens to take them (Rawles, '48). The present studies provide abundant evidence that some cells can, and in many species do, differentiate into fully defined chromatophores well in advance of their departure from the neural crest region. The different patterns of migration and aggregation of different kinds of pigment cells, as in the Pacific Mackerel, also support the idea that migratory routes and destinations depend on the type of cell rather than the reverse. The actual migratory pathways of chromatophores are also difficult to study in other vertebrates and are little understood, but should be easy to trace by simple histological methods in such teleosts as the Pacific Sardine and Pacific Mackerel.

Larvae of marine fishes are notoriously difficult to keep alive for more than a few days after hatching, but this is no obstacle to the type of studies reported here, since the basic pigment characters become well established within this period. Furthermore, careful laboratory techniques and investigation into food requirements should prolong the viable period.

A thorough analysis of chromatophore embryology and early pattern history in fishes is much needed, and would be of basic importance to taxonomists as well as to embryologists and pigment cell specialists. The simple observations on pelagic marine teleosts reported here should suggest many obvious problems for which this type of material is unusually well suited.

## SUMMARY

The neural crest theory of the origin of vertebrate pigment cells was established by extensive experimental work, chiefly on amphibians and higher vertebrates. Relatively little has been done on the early history of chromatophores in fishes, and only recently (Lopashov, '44; Newth, '51) has there been experimental evidence to show that pigment cells in this group are also derived from the neural crest. The suggestion by Borcea ('09) that teleost chromatophores develop from ectodermal cells in the neural crest region was based on several marine fishes, chiefly with pelagic eggs, but the significance of the visible migration of pigmented cells that he reported has very largely been overlooked or misunderstood by subsequent investigators.

Observations on pigment development in living embryos and larvae of more than 40 species of California marine fishes, of which representatives are described in detail, indicate that chromatophores, especially black cells, commonly become pigmented very early in their development, and that the extreme

transparency of the living embryo and larva makes both the primary location and the subsequent history of these cells easily traced. In nearly all species studied thus far, but preeminently in those with small, rapidly-developing pelagic eggs, there is a primary pigmentation center along the dorsal and/or dorsolateral surfaces of the body and tail, i.e., along the neural crest region, from whence the cells migrate, chiefly downward, to secondary positions. The stage at which pigment forms in the cells determines the ease with which the migratory process can be followed in the transparent living specimen. In species in which visible pigment forms before the cells disperse from the neural crest region, the entire course of migration is open to view. It is especially well shown in the Pacific Sardine. In the advanced embryo and newly hatched larva of this fish, small but clearly visible black cells are arranged in a pair of rows along the dorsolateral surfaces of the body and tail; soon after hatching the cells enlarge and become strongly amoeboid, and can be seen in various stages of progress downward over the sides of the somites to new positions in two rows along the upper (anterior) and lower (posterior) surfaces of the very long body cavity. At room temperature, the process is essentially completed within two days after hatching. In several other species described here, early pigment development follows the same basic plan but the details are somewhat more complicated. In some additional species, e.g., the Opaleye and various anchovies, the cells do not become visible until their probable dispersal is more or less complete, and in still others, e.g., the Diamond Turbot, events are somewhat obscured by the great abundance of the chromatophores that develop.

In the pelagic species studied thus far, the conspicuous first wave of cell migration is typically completed within two days after hatching, and establishes a relatively fixed basic color pattern that many species retain throughout larval life, which may be of several months' duration. The time available for formation and dispersal of pigment cells from the expendable neural crest is limited, hence it seems probable that the transitory visible migration of relatively small numbers of pigmented cells in these fishes is accompanied or soon followed by additional waves of undifferentiated pigment cells that tend to remain colorless until metamorphosis, as has been demonstrated experimentally in salamanders. Since the initial migration in pelagic teleosts is very brief, as well as variably distinct in different species, it is not surprising that its interpretive possibilities appear to have been overlooked by embryologists.

The characteristics of chromatophore development that can be followed *in vivo* in certain marine teleosts with pelagic eggs strongly support the concept that pigment cells originate in the neural crest region in fishes as well as in tetrapod vertebrates, and provide a far more graphic, living demonstration of the dynamics of cell migration than could be obtained from experimental or histological studies alone. These exceptionally clear characteristics are brought to the attention of pigment cell specialists in the hope of stimulating more detailed research on this type of teleost material.

## LITERATURE CITED

AGASSIZ, A., AND C. O. WHITMAN 1885 The development of osseous fishes. I. The pelagic stages of young fishes. Mem. Mus. Comp. Zool., *14:* 1–56.

BOLIN, R. L. 1930 Embryonic development of the labrid fish, *Oxyjulis californicus* Günther. Copeia, 1930 (4): 122–128.

——— 1936 Embryonic and early larval stages of the California anchovy, *Engraulis mordax* Girard. Calif. Fish and Game, *22:* 314–321.

BORCEA, I. 1909 Sur l'origine du coeur, des cellules vasculaires migratrices et des cellules pigmentaires chez les Téléostéens. C. R. Acad. Sci. Paris, *149:* 688–689.

CUNNINGHAM, J. T. 1889 Studies of the reproduction and development of teleostean fishes occurring in the neighbourhood of Plymouth. J. Mar. Biol. Assn. U. K., n.s., *1:* 10–54.

——— 1891 On some larval stages of fishes. J. Mar. Biol. Assn. U. K., n.s., *2:* 68–74.

DUSHANE, G. P. 1943 The embryology of vertebrate pigment cells. Pt. 1. Amphibia. Quart. Rev. Biol., *18* (2): 109–127.

——— 1948 The development of pigment cells in vertebrates. Spec. Publ. N. Y. Acad. Sci., *4:* 1–14.

FRY, D. H., JR. 1936 A description of the eggs and larvae of the Pacific mackerel. Calif. Fish and Game, *22:* 27–29.

GOODRICH, H. B. 1950 Problems of origin and migration of pigment cells in fish. Zoologica, *35:* 17–19.

HOLT, E. W. L. 1893 Survey of fishing grounds, west coast of Ireland, II 1890–91. On the eggs and larval and post-larval stages of teleosteans. Sci. Trans. Roy. Dubl. Soc., (2) *5:* 5–121.

HÖRSTADIUS, S. 1950 The neural crest — its properties and derivatives in the light of experimental research. Oxford Univ. Press, viii + 111 pp.

KUNTZ, A., AND L. RADCLIFFE 1917 Notes on the embryology and larval development of twelve teleostean fishes. Bull. Bur. Fish., *35* (for 1915–16): 87–134.

LOPASHOV, G. V. 1944 Origin of pigment cells and visceral cartilage in teleosts. C. R. Acad. Sci. U.R.S.S., n.s., *44* (4): 169–172.

MCINTOSH, W. C., AND A. T. MASTERMAN 1897 The life-histories of British marine food-fishes. London, C. J. Clay and Sons: xvi + 516 pp.

MILLER, D. J. 1952 Development through the prolarval stage of artificially fertilized eggs of the Pacific sardine *(Sardinops caerulea).* Calif. Fish and Game, *38:* 587–595.

NEWTH, D. R. 1951 Experiments on the neural crest of the lamprey embryo. J. Exp. Biol., *28:* 247–260.

OPPENHEIMER, JANE M. 1950 Atypical pigment cell differentiation in embryonic teleostean grafts and isolates. Zoologica, *35:* 22–23.

RAWLES, MARY E. 1948 Origin of melanophores and their role in development of color patterns in vertebrates. Physiol. Rev., *28:* 383–408.

RYDER, J. A. 1882 Development of the Spanish mackerel *(Cybium maculatum).* Bull. U. S. Fish Comm., *1:* 135–172.

——— 1884 A contribution to the embryography of osseous fishes, with special reference to the development of the cod *(Gadus morrhua).* Ann. Dept. Comm. Fish. for 1882: 455–605.

TWITTY, V. C. 1936 Correlated genetic and embryological experiments on Triturus. I and II. J. Exp. Zool., *74:* 239–302.

——— 1949 Developmental analysis of amphibian pigmentation. Growth Sympos., *9:* 133–161.

TWITTY, V. C., AND D. BODENSTEIN 1939 Correlated genetic and embryological experiments on Triturus. III and IV. J. Exp. Zool., *81:* 357–398.

# PLATE 1

## EXPLANATION OF FIGURES

Pigment cell migration in the Pacific Sardine, *Sardinops caerulea*

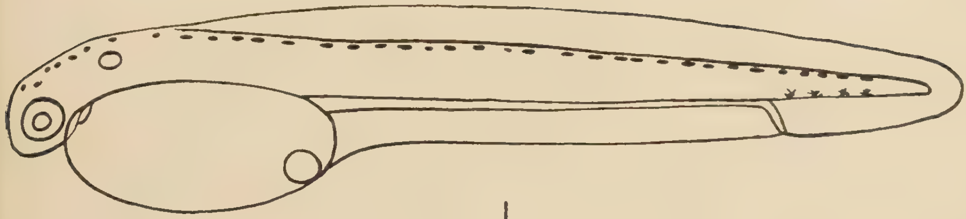
1 Newly hatched larva. Melanophores develop visible pigment before migrating from neural crest region; at this stage most of the cells are still aligned in a pair of dorsolateral rows.

2–3 Larvae one day old. Amoeboid melanophores are migrating downward over sides of somites.

4 Larva two days old. Basic larval pattern becoming established; most of the melanophores have reached new positions in two parallel rows bordering upper surface of body cavity anteriorly and its lower surface posteriorly.

5 Larva three days old. Shows further progress in structural development but little change in pigmentation.

Note: All figures on plates are semi-diagrammatic; notochord, somites, contour stippling, and other details that might be confused with or obscure the pigment cells are omitted.



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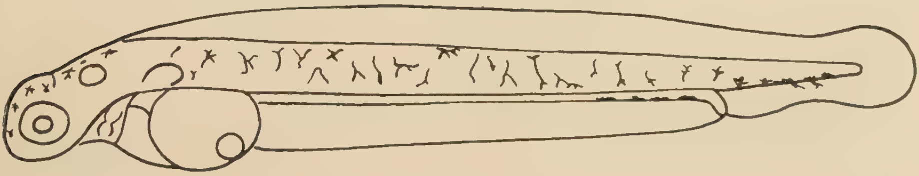

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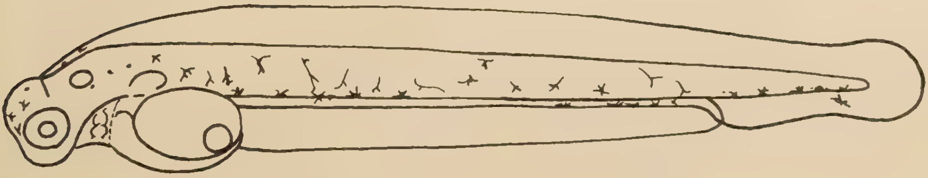

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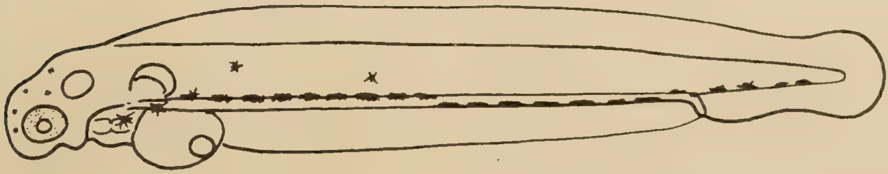

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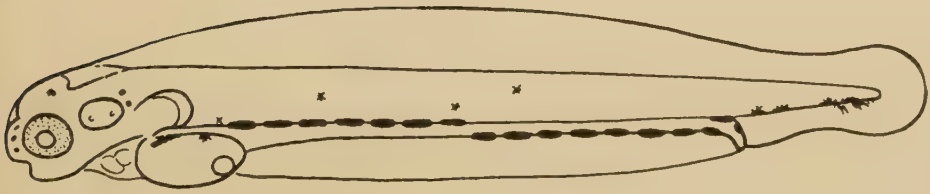

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# PLATE 2

## EXPLANATION OF FIGURES

Pigment cell migration in the Sheephead, *Pimelometopon pulchrum*

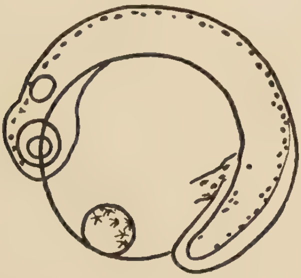
6–7 Two embryonic stages, the latter near hatching. As in the Pacific Sardine, melanophores acquire visible pigment before migrating from neural crest region, and appear first in a pair of rows along dorsolateral surfaces.

8 Newly hatched larva. Melanophores beginning to disperse from the two rows in neural crest region.

9 Larva one day old. Melanophores moving downward and assembling along ventrolateral surfaces of somites.

10 Larva two days old. Basic larval pattern well established.

11 Larva three days old. Further advancement in structural development, but little change in pigmentation.



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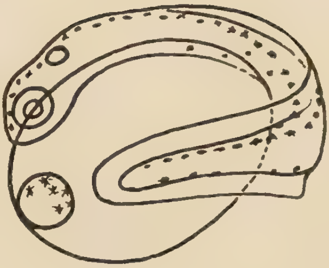

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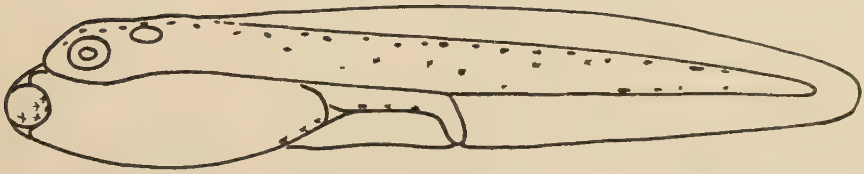

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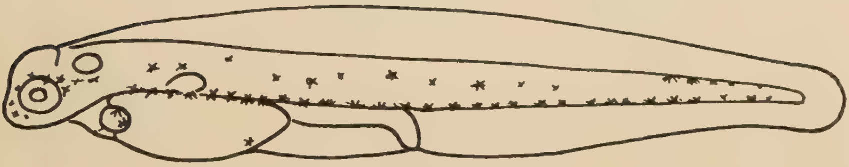

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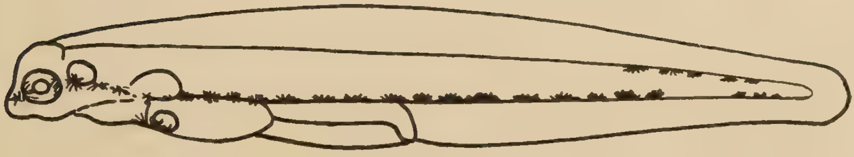

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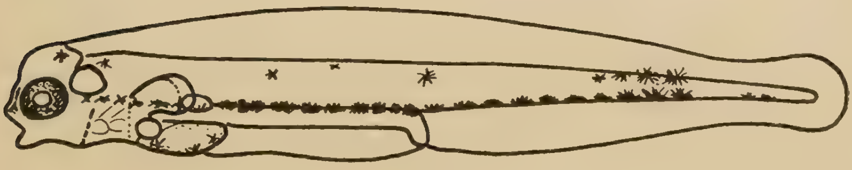

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# PLATE 3

## EXPLANATION OF FIGURES

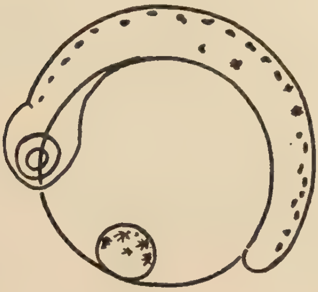
Pigment cell migration in the Señorita, *Oxyjulis californica*

12–13 Two embryonic stages, the latter nearing hatching. Melanophores acquire black pigment before migrating from neural crest region; when first visible they form two rows along dorsolateral surfaces.

14 Newly hatched larva. Melanophores beginning to disperse from dorsolateral rows.

15 Larva one day old. Melanophores aggregating into blotches along body cavity and tail.

16 Larva 4 days old. First wave of migration completed, larval pattern well established; melanophores heavily massed in two large blotches on tail and one above angle of hindgut.



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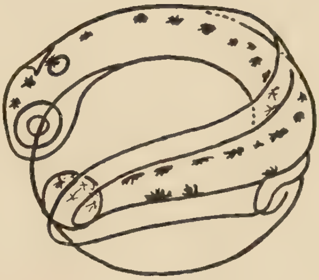

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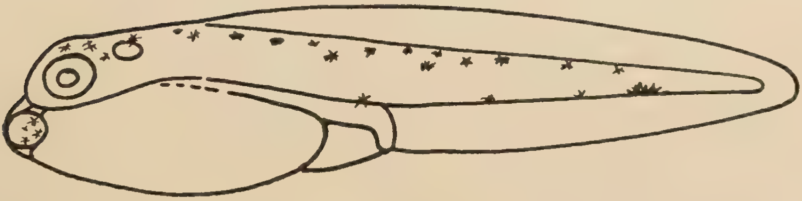

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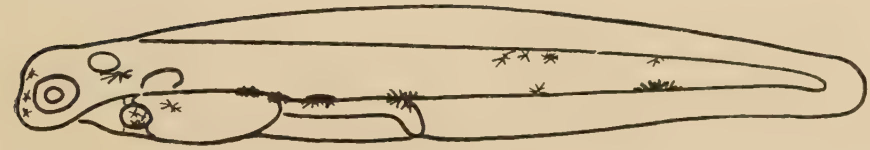

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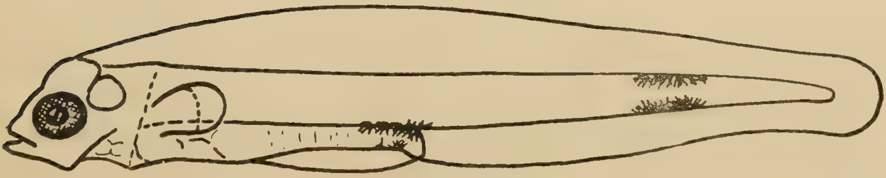

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# PLATE 4

## EXPLANATION OF FIGURES

Pigment cell migration in the Pacific Mackerel,

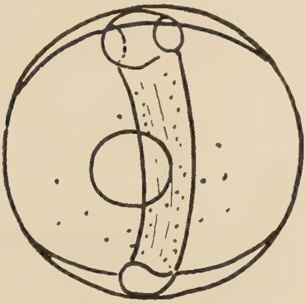
*Pneumatophorus japonicus diego*

17–18 Two embryonic stages, the latter near hatching. Both black and yellow pigment cells develop, and the two types aggregate independently. In early embryo small grayish cells appear on dorsal and dorsolateral surfaces; in advanced embryo black cells are chiefly in pair of dorsolateral rows, and yellow cells are grouped in pattern of large blotches (indicated by finely stippled areas).

19 Larva a few hours after hatching. Melanophores migrating downward and aggregating along lower edges of somites and top of body cavity; little change in pattern of yellow cells.

20 Larva one day old. Migration of melanophores nearly completed; yellow band on tail dispersing.

21 Larva two days old. First wave of melanophore migration completed; yellow pigment has disappeared from tail, yellow areas on head and trunk are diffuse.



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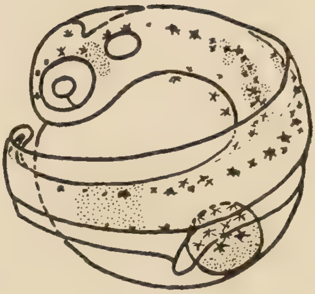

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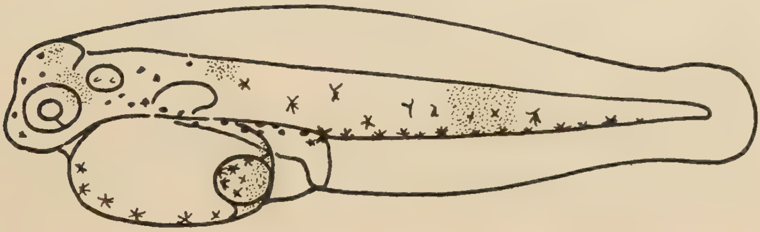

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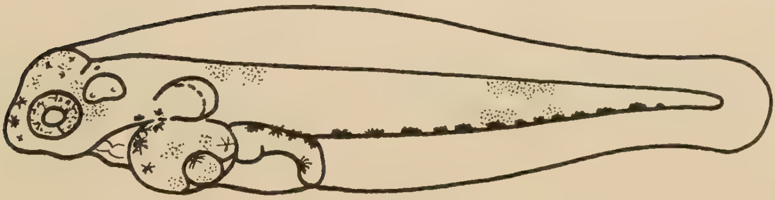

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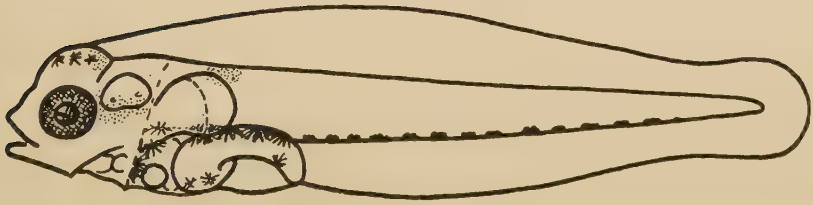

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## PLATE 5

### EXPLANATION OF FIGURES

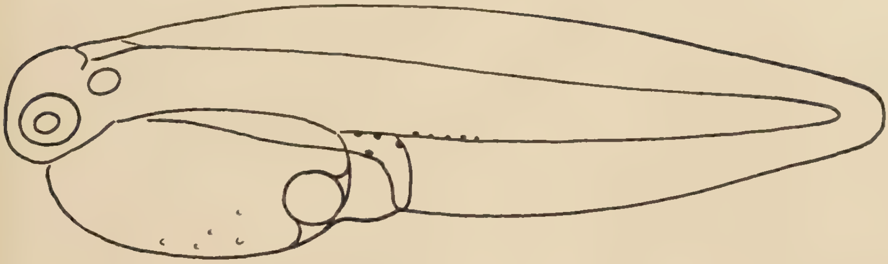
Pigment cell development in the Opaleye, *Girella nigricans*

22 Newly hatched larva. Pigment cell history differs from that in other species illustrated; migration of pigment cells from neural crest region is not apparent in Opaleye; the melanophores are already in secondary positions when they become visibly pigmented.

23 Larva one day old. Small melanophores abundant, especially along lower edges of somites and top of body cavity.

24 Larva two days old. Pattern essentially the same but melanophores larger, more highly branched, and probably have begun to aggregate.

25 Larva three days old. Larval pattern well established. Melanophores heavily massed along top of body cavity and in series of large spots along mid-ventral edge of tail; additional melanophores have appeared, especially along dorsal surfaces.



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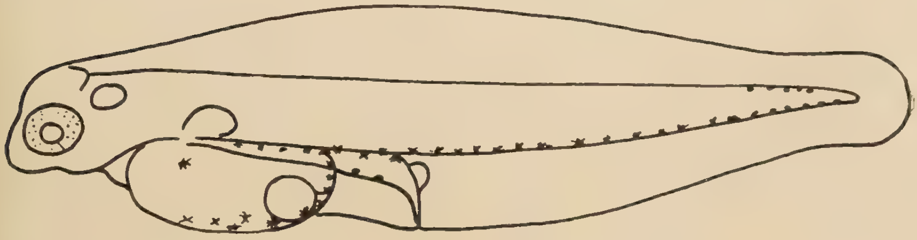

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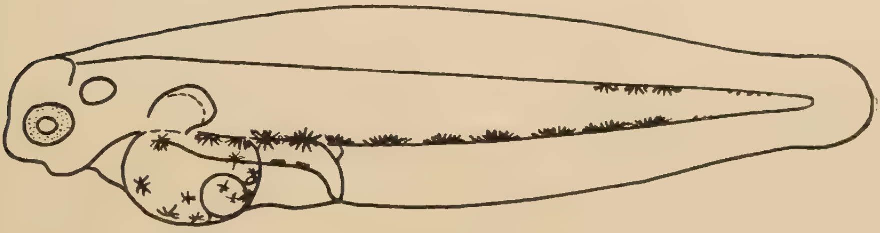

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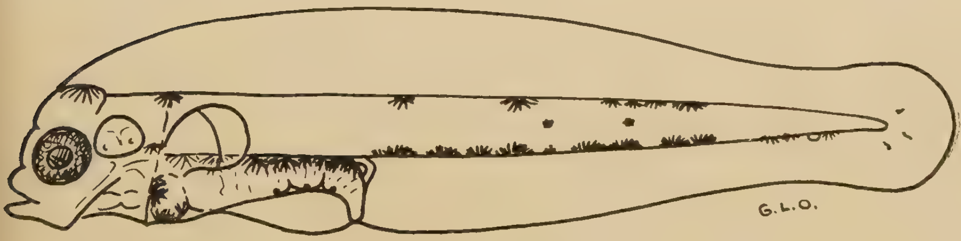

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# An Improved Graphical Analysis and Comparison of Series of Samples

CARL L. HUBBS and CLARK HUBBS

OVER the past few decades graphical methods have been developed and increasingly used for the comprehensive analysis and for the rapid and economical comparison of series of samples. These methods are applicable to any type of data involving random variation, but are of particular concern to systematists, who are constantly confronted with data derived from series of varying samples.

In his pioneering study of variation and speciation in the garter snakes (*Thamnophis*), Ruthven (1908) showed by graphs the range, the mean, and the number of specimens for the scale counts of each of several geographically arranged groupings. He indicated the ranges by vertical lines on which the means were located by symbol according to sex. The means were connected so as to portray the variational trends (now called clines). This presentation was useful and promising, but failed to indicate the significance of the observed differences or to give more than the crudest idea of the degree of overlap or separation between samples.

A valuable and clever addition to Ruthven's format was proposed by Dice and Leraas (1936). In each vertical line showing the range and the mean for a sample they inserted a rectangular bar, like those in Figure 1, outlining two standard errors of the mean ($2\sigma_M$) on either side of the mean. This method was designed to indicate and to test the significance of the difference between the means of each pair of samples portrayed. It was shown that the level of "significance" arbitrarily adopted by biologists was just about satisfied when two rectangles met, end to end, on the same horizontal.

Following the same lead, Hubbs and Perlmutter (1942) pointed out that "this is a special case; we need some indication too of the significance of the differences (*t* values), corresponding to the varying relative lengths, and to the varying overlap or separation, of the rectangles." Though many biologists and some statisticians still accept such an arbitrary distinction, there is no magic line (as $P = .05$ or .01), where totally unreliable evidence suddenly gives way to completely trustworthy indications of significant difference (see Figure 4).

With the aid of biometrician Charles W. Cotterman, Hubbs and Perlmutter indicated in tabular form just what degree of reliability can be attributed to data showing, when graphed as in Figure 1, varying degrees of overlap or of separation between the bars outlining $2\sigma_M$ on either side of the mean. They concluded that considerable reliance can be placed on the significance of the difference between samples, if the corresponding rectangles are only slightly separated, or if the overlap is not more than about 33 per cent of the length of the shorter of the two rectangles. When the longer rectangle is 2 to 4 or more times as long as the shorter one, an overlap of 50 per cent or even 75 per cent does not negate the probability that a significant difference exists. If the gap between the rectangles exceeds 10 per cent of the length of the shorter, the significance of the difference between the populations may be regarded as demonstrated beyond any reasonable doubt (if we assume the samples to be representative).

When the overlap of two subequal rectangles exceeds one third of the length of the shorter rectangle, little or no reliance can rightly be placed on the significance of the difference. When the overlap is 50 per cent the odds of significance are less than 10 to 1 unless the length of one rectangle is more

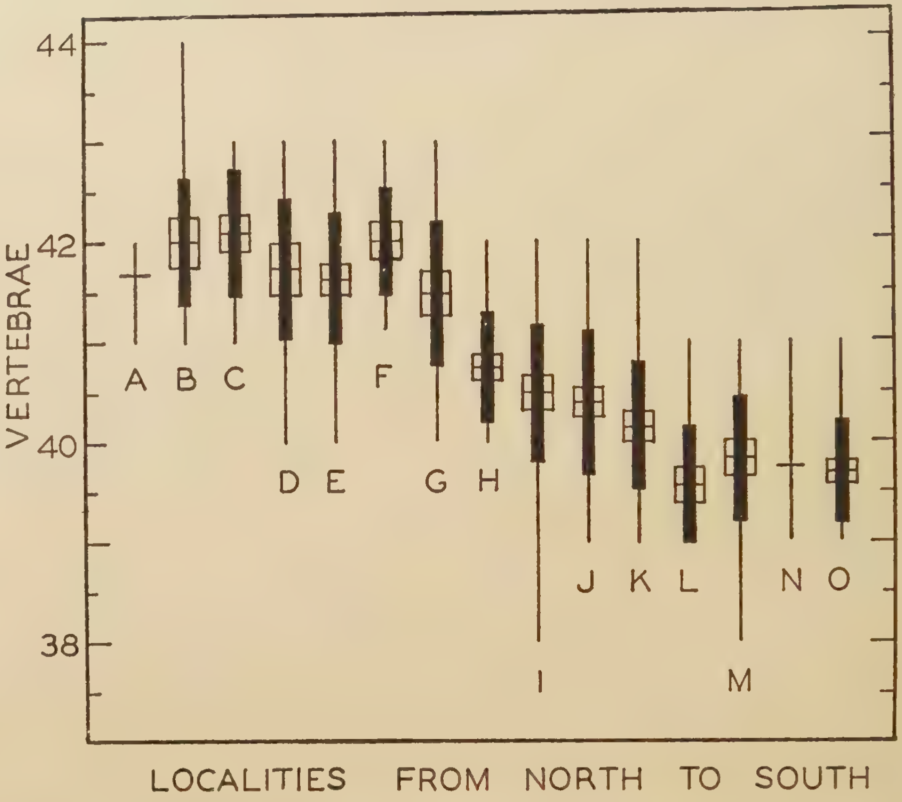

FIG. 1. Variation from north to south in the number of vertebrae of the anchovy, *Anchoviella mitchilli.*

A, Massachusetts (3 specimens); B, Great Peconic Bay, New York (25); C, Hudson River, New York (50); D, Great South Bay, New York (30); E, New Jersey north of Cape May (63); F, Cape May, New Jersey (30); G, Mount Landing, Virginia (48); H, Charleston Harbor, South Carolina (77); I, Georgia (64); J. eastern Florida (95); K, western peninsular Florida (77); L, St. Andrews Bay, Florida (50); M. Texas (47); N, Río Papaloapam, Mexico (8); O, Yucatán (100). See text for a description of the graph.

FIG. 1. Reproduction of figure presented by Hubbs and Perlmutter (1942) to illustra their modification of the Dice and Leraas method for the graphical comparison of series samples. Subsequent workers have portrayed the standard deviation ($\sigma$) on either side mean as a narrow hollow bar.

han 4 times that of the other. Such differnces in the values for $\sigma_M$ are very rare in omparable data. Ordinarily any very considrable overlap renders the significance of the ifference very doubtful.

Hubbs and Perlmutter further modified he graphical method by adding to the iagram for each sample (see Figure 1) a neasure of dispersion ($\sigma$, the standard eviation). This parameter nicely supplenented the measure of reliability ($2\sigma_M$) ntroduced by Dice and Leraas. The disinction between these two measures, hough still far from being universally ppreciated, is of great importance. The tandard deviation measures dispersion bout the mean. Its values, except for uctuations induced by very small samles, do not vary with the size of the samle. The values for $\sigma_M$, on the contrary, ear on the reliability of the data and ary inversely with the square-root of the umber of variates. Hubbs and Perlmuter noted:

> When two samples showing normal variaon are compared, an overlap in the frequenies of about 16 per cent only is indicated hen the broad bars representing the standrd deviations neither overlap nor are sepaated on the ordinate scale. That is, about 84 er cent of the specimens of both categories would then be separable, in that their values for the given character would lie on the proper side of the line best separating the two populations. Such differences are approximately of the order that may be utilized for subspecific separation.

A number of authors, representing botany and paleontology as well as several fields of zoology, have utilized the graphical method successively elaborated by Ruthven, Dice and Leraas, and Hubbs and Perlmutter. Some, as Hubbs and Hubbs (1947), Pitelka (1950), Tordoff (1952), and Storer (1952), have modified the drafting format. It became apparent that the use of a hollow instead of a black bar to embrace $\sigma$ on either side of the mean was necessitated by the circumstance that at times the value for $\sigma$ transgresses in one direction the observed range. Ordinarily, the bars representing $2\sigma_M$, or this value and $\sigma$, on either side of the mean, have been drawn, more or less as in Figure 1, awkwardly straddling the line indicating the range of variation; and the lines have been kept vertical by most authors.

When confronted with the need of presenting by some such method a large amount of data, in part involving long series of samples, the junior author found

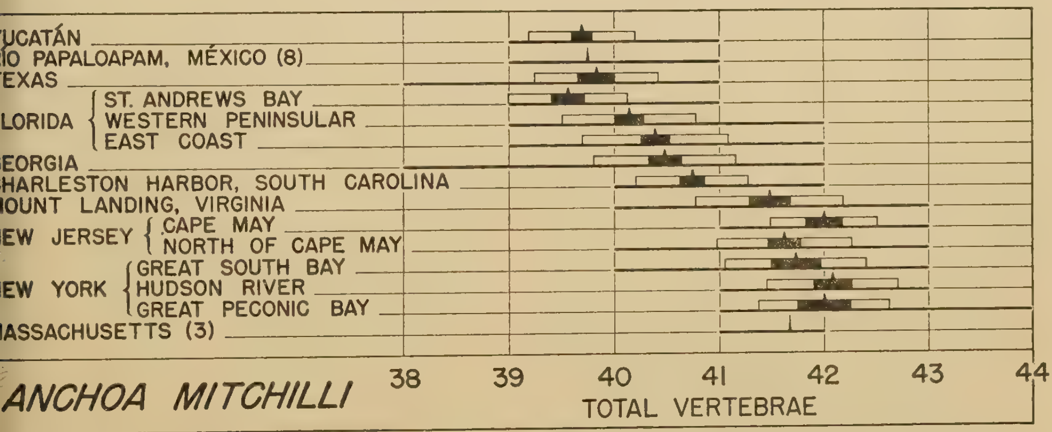

Fig. 2. Regraphing by new format of the same data shown in Fig. 1. Drafted by Robert . Kirk. The guidelines are very helpful but not essential. For each locality the range of ariation is shown by a heavy horizontal line; the mean (*M*), by a small, narrow triangle. he blackened part of each bar comprises 2 standard errors of the mean ($2\sigma_M$) on either side *M*. One-half of each black bar plus the white bar at either end outline 1 standard deviation ) on either side of *M*. $\sigma$ indicates dispersion; 2 $\sigma_M$, reliability.

the previously used graphical techniques time-consuming and in some ways inadequate. The authors together then reconsidered the mode of presentation and arrived at a simple and, we think, otherwise better format. The modified method, which presents the same parameters that were graphed by Hubbs and Perlmutter, has been used by the junior author repeatedly in his recent monographs (Hubbs, 1952 and 1953) on the clinid fishes and in other contributions in press, and has been adopted by the senior author in several papers now in preparation. Through personal contacts some publicity has been given to the improved method.

The differences between the two drafting techniques become evident on comparing Figure 1 (Hubbs and Perlmutter's test case) with Figure 2, which presents the same data much more simply. The basic differences lie in the elimination of a useless half of each bar and in the horizontal alignment of each diagram. Oliver (1948, p. 180) also used the unilateral form on a horizontal basis, but did not include the bar for $\sigma$.

Following are advantages of the method:

1. The horizontal alignment (*a*) facilitates comparisons, (*b*) renders more facile and satisfactory the inclusion on the graph of such data as the localities given on Figure 2, and (*c*) is more quickly grasped, because it is conventional in presenting such data by frequency tables or graphs, and somewhat suggests a frequency curve.
2. The data are more compact. The vertical space occupied by the new graph, per unit of width, is 45 per cent of that of the prior graph, or only 36 per cent if account be taken of the inclusion within the new format of the geographical data that required a long sublegend in the old. Twice as many samples can be compared in a full-page graph.
3. The drafting is easier, in that each unit requires only 7 lines (or 6 lines plus a small triangle quickly mac with the templet for *W* on a lette ing guide), instead of 10 lines, ar has fewer close-set parallel line slight misplacements of which a glaring.
4. The simpler bars facilitate the reco nition of $\sigma$ and of $2\sigma_M$ and rend more apparent the degree of ove lap, or separation, of the bars.
5. The darkening of the central (stan ard-error) bars emphasizes the va ues that most often call for compar son.
6. The greater simplicity adds to tl attractiveness of the diagram.
7. The new graphical method allov two diagrams to be drawn on eith side of a line (one up and the oth down, or one to left, the other right), as for expressing fluctuatio of proportions at several differe lengths of a fish.

Usually the bars covering $4\sigma_M$ will blackened in, but occasionally, as wh superimposed over a scatter diagram, tl bars will need to be stippled, cros hatched, or otherwise shaded, so as not conceal underlying symbols. When se eral sets of data are repeated on the sar graph, it may be desirable to identify diagrams pertaining to the same series ( species) by a distinctive type of shadir Such a graph could have several cluste of diagrams, in each of which one diagra would have the standard-error bar st pled, another cross-hatched, another st pled, and so on.

An innovation in Figure 2, the lig guidelines, will facilitate examination a will often eliminate the need for using square to determine whether or ho much the bars of distant units overlap are separated.

Through representation by a heavy lin now at the bottom of each unit, the ran can be made to stand out even when happens to be overlapped on one side the mean by the outer (white) part of t bar representing $\sigma$, or even (in very

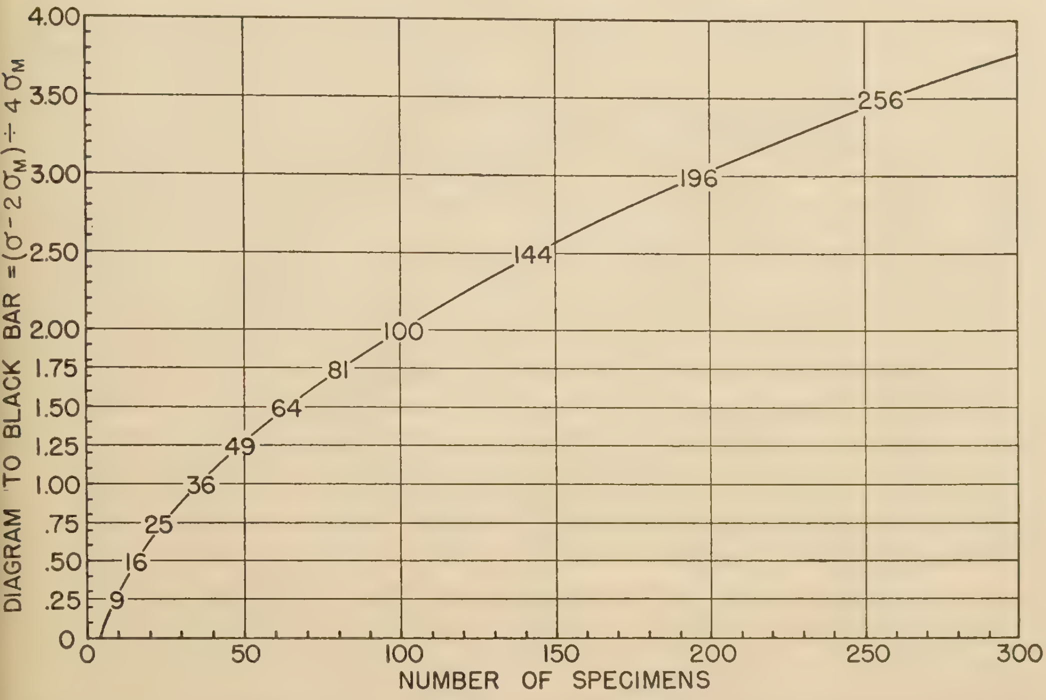

FIG. 3. Data for estimation of number of specimens in each sample from graphs like ig. 2. Drafted by Robert W. Kirk.

eptional cases) by the dark bar portray-ng $2\sigma_M$.

Some authors have indicated on their raphs the number of specimens for each ample. This could have been done in arentheses following the legends on the eft side of Figure 2. It is hardly neces-ary, however, to specify the numbers, for f we keep in mind the numerical relation-hip between $\sigma$ and $2\sigma_M$, we can by inspec-ion of the graph approximate the num-er of specimens in each lot. The differ-nce is proportional to that between $N$ nd $2\sqrt{N}$. Thus, if there are 4 specimens, he two bars of the diagram will coincide, ince $4=2\sqrt{4}$. For the simplest visual esti-nate of the number of specimens we may ompare the ratio in lengths between the vhite bar at either end of each diagram n Figure 2 $(\sigma-2\sigma_M)$ and the entire dark ar $(4\sigma_M)$. It can readily be computed hat the sample comprises 9 specimens vhen the white bar is one-fourth as long s the dark bar; 16 when one-half as long; 25 when three-fourths as long; 36 when of equal length; 49 when one-fourth longer; 64 when one-half longer; and so on. These values are indicated on Figure 3, which allows for ready interpolation. When the values for $\sigma$ have been rounded off, the estimates of number of specimens lose some precision, but are sufficiently accurate.

Since for most purposes the statistical parameters vary little for samples of more than 30 specimens and remain nearly constant for samples of more than 100, graphs constructed in the style of Figure 2 indicate at a glance that statistical adequacy is approached when either white end-bar exceeds the dark bar in length, and is ordinarily fully attained when the white bar is more than twice as long as the dark. When the white bar is much shorter than the dark, the values for that sample cannot be regarded with much confidence. It is recommended that only the range and the mean be indicated when 9 or fewer specimens are involved and when, as a result, the length of the white bar would be only one-fourth, or less than one-fourth, the dark one. For such entries the number of specimens may be indicated on the graph.

When the samples include fewer than 30 specimens there are other reasons for distrusting the reliability of the difference that is indicated by the graphical method. The values for σ are calculated on the assumption of normal distribution, not likely to be realized in small samples, and the values for *t* (considered below) are calculated by the conventional large-sample formula (as indicated by Hubbs and Perlmutter). For comparisons of small series, statitisticians favor a formula designed for such samples, such as the "Student" *t* test. For especially critical comparisons of samples having fewer than 30 specimens, the use of such a formula is recommended.

Since the length of the dark bar and its limits are of critical significance in the graphical interpretation, the drafting should be precise, and the outer edge of the bar to be inked in should be run on the exact limit.

The criticisms levied against the Dice-Leraas method by Simpson and Roe (1939, pp. 316-320) would apply with equal force against the proposed modification, but were answered, we think adequately, by Hubbs and Perlmutter. We regard the method as sufficiently valid and precise for most biological applications. With the inclusion of a bar to represent the standard deviation (σ), but not of the often transgressed "theoretical ranges ($M \pm 3\sigma$)" proposed by Simpson and Roe, the method, especially when graphically refined as here proposed, provides an adequate means of publishing data that would be less readily understood and very space-consuming and cumbersome to present in tabular form.

We now offer in one graph (Figure 4), rather than in two tables, as Hubbs and Perlmutter did, an improved means for determining, very quickly and without
any involved calculations, the probab
significance of the observed differenc
between any two samples in a seri
plotted as in Figure 2. The graphical an
ysis follows a simple procedure. First, o
estimates roughly (for high precision
unnecessary and hardly justified) the
tio of the lengths of the two pertine
dark bars, each representing $4\sigma_M$. Th
estimate can be made rather adequate
by mere inspection; better by steppi
with dividers, the shorter dark bar i
the longer. From the ratio thus obtain
one selects the appropriate straight li
as labeled on the right margin of Figu
4, or interpolates between two of the
lines. Next, one estimates approximate
—visual inspection or a quick manipu
tion of the dividers suffices—the overl
or separation of the two bars, express
as a percentage of the length of the shor
bar. Then, from the ascertained perce
age scaled on the lower margin one rea
up to the chosen straight line, or point
interpolation, and on the horizontal th
located reads off, on the left margin,
approximate and sufficiently precise
value (the ratio of the difference betwe
the means to the standard error of t
difference). The odds of significance c
responding to certain *t* values, also
corded on the left margin, give an appr
imate idea of the significance of the diff
ence. To obtain the value of *P* (the c
ventional expression of the probabil
that the observed difference is due
chance), one follows the horizontal li
located as indicated above, to the hea
line labeled *P* and reads off the cor
sponding *P* value as scaled along the
per margin. If one prefers to think
other terms, it is possible to comp
quickly the odds of significance from
formula $(1-P) \div P$.

The graphical analysis rendered by F
ure 4 makes it clearly obvious why
broad overlap of the dark bars indica
low reliability of the observed differe
between two samples and why any c
siderable separation of these bars i
cates a high reliability. The sloping li

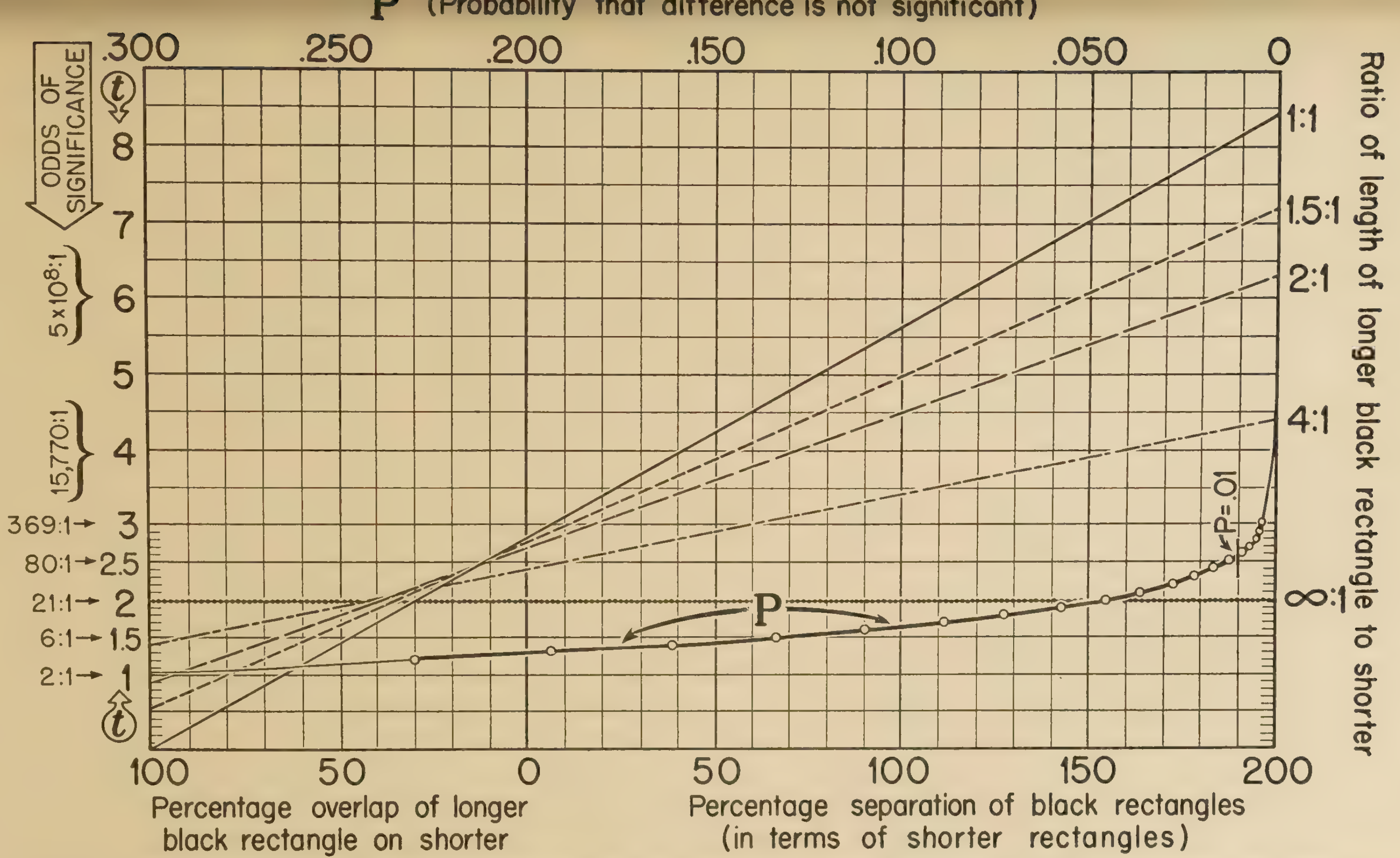

FIG. 4. Graphical analysis of the difference between any two samples graphed in the style of Fig. 2. Prepared from data presented by Hubbs and Perlmutter (1942, Tables I and II). Drafted by William L. Brudon. The straight lines are read against the left margin and the bottom of the graph; the heavy *P* line, against the left margin and the top. For procedure in using graph, see text.

representing the ordinary fluctuations in the relative lengths of the two dark bars intercept the vertical line of neither overlap nor separation (0 on the graph) at points corresponding with the narrow region where the $P$ curve is very abruptly inflected.

A word of caution may be intercalated regarding the degree of confidence to be placed in the measures of reliability, especially when the values for $t$ are very high (or those for $P$ are very low). The computations of these measures are based on assumptions, including the normal distribution of variates, that may not be completely justified. All such computations are subject to fluctuation and should be treated as approximations. High values of $t$ are trustworthy and low values unreliable, much as is indicated in the preceding discussion, but not to the exact degree indicated. The probability of divergent samples in biology representing similar populations is likely to be rather greater than is indicated by the conventional computations, for the frequency curves tail out on either side more extensively than would be indicated by the statistical theory. The chances of unusual values unexpectedly appearing are often greater in biological than in other data, because of the complex factors involved.

When used with reasonable reserve, however, the methods here presented for the graphical analysis and comparison of series of samples are highly efficacious and economical and are adequate for most purposes in systematics and other fields of biology. These methods permit rapid and comprehensive comparisons; well portray similarities, differences, and trends; and indicate with sufficient precision the degree of divergence between samples and the reliability of the indicated distinctions. Ordinarily, higher precision is not needed, and, indeed, is often unjustified.

## *Addendum*

The method proposed by Hubbs an Perlmutter has been presented by May Linsley, and Usinger in their book o the *Methods and Principles of Systemat Zoology* (McGraw-Hill Book Co., 1953; p 142-150, Fig. 26). They suggest, howeve the plotting of 1.5$\sigma$ on either side of th mean, instead of 1.0$\sigma$, in order "to indica probable subspecific difference" by a no overlap of the bars. Neither overlap n separation of the bars representing 1. would indicate, with normal distribution the separability of 93 per cent of the spec mens. The same authors, however, els where recommend a value of 1.28$\sigma$ indicating "the conventional level of su specific difference" (90 per cent separ tion). Both values seem higher than tho usually accepted (0.675$\sigma$ and 75 per cent Our recommended plotting of 1.0$\sigma$ either side of the mean, indicating an per cent separation, seems to us qui adequate.

In view of the obvious advantages plotting the data recommended by Hub and Perlmutter, we disagree with the dication by Cazier and Bacon, in the "I troduction to Quantitative Systematic (*Bull. Am. Mus. Nat. Hist., 93,* 383-3 Fig. 12), that for usual systematic pu poses it is sufficient to plot the mea the observed range, and the "calculat range" (3$\sigma$).

## REFERENCES

DICE, L. R., and LERAAS, H. J. 1936. A grap method for comparing several sets of me urements. *Contr. Lab. Vert. Gen. Un Mich.*, No. 3.

HUBBS, CARL L., and HUBBS, LAURA C. 19 Natural hybrids between two species catostomid fishes. *Pap. Mich. Acad. S Arts, and Letters, 31* (1945), 147–167.

HUBBS, CARL L., and PERLMUTTER, A. 19 Biometric comparison of several samp with particular reference to racial inve gations. *Am. Naturalist, 76,* 582–592.

**An Improved Graphical Analysis**

Hubbs, Clark. 1952. A contribution to the classification of the blennioid fishes of the family Clinidae, with a partial synopsis of the Eastern Pacific forms. *Stanford Ichth. Bull., 4,* 41–165.

——— 1953. Revision and systematic position of the blenniid fishes of the genus *Neoclinus. Copeia,* 1953, 11–23.

Oliver, J. A. 1948. The relationships and zoogeography of the genus *Thalerophis* Oliver. *Bull. Am. Mus. Nat. Hist., 92,* 157–280.

Pitelka, F. A. 1950. Geographic variation and the species problem in the shore-bird genus *Limnodromus. Univ. Calif. Publ. Zool., 50,* 1–108.

Ruthven, A. G. 1908. Variation and genetic relationships of the garter-snakes. *U. S. Nat. Mus. Bull.* 61.

Simpson, G. G., and Roe, Anne. 1939. Quantitative zoology. McGraw-Hill Book Co., New York and London.

Storer, R. W. 1952. A comparison of variation, behavior and evolution in the sea bird genera *Uria* and *Cepphus. Univ. Calif. Publ. Zool., 52,* 121–222.

Tordoff, H. B. 1952. Notes on plumages, molts, and age variation of the red crossbill. *Condor, 54,* 200–203.

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# The Influence of Light on the Number of Vertebrae in the Grunion, *Leuresthes tenuis*[1]

J. L. McHUGH

IT is well known that the mean numbers of vertebrae in fishes can be influenced by environmental factors, notably temperature and alinity, during the early developmental stages Schmidt, 1918, 1919, 1920, 1921; Tåning, 944, 1952; Heuts, 1946). Undoubtedly other nvironmental factors produce similar effects Vladykov, 1934; Johnsen, 1936), although nvestigations along these lines have not been xtensive. Dannevig (1932) has suggested that he number of vertebrae in the cod may be nfluenced by light intensity, and it has been tated (Worth, 1898) that the hatching of shad ggs is speeded in direct sunshine, and that ontinuous dark and cloudy days will retard, nd strong light will accelerate, development nder equal conditions of temperature. Willer 1928) also has found that light affects the ate of development of fishes. More recently, oover and Hubbard (1937) have found that he sexual cycle in trout can be modified by ontrol of light, and this knowledge has been put to practical use by the Fish and Game Department of New Hampshire (Bernard W. Corson, personal communication).

The experimental results reported here can not be considered conclusive. Nevertheless, they bear on the results of investigations shortly to be reported, and add to the scanty literature relating to the effect of light on animal development. The experiments were designed originally to determine the effects of temperature and salinity on mean vertebral number in the grunion, *Leuresthes tenuis* (Ayres). It soon became apparent that the results were too variable to be of value for this purpose. In searching for the cause of this variability, it was realized that the amount of light falling on the experimental lots was not under control, and a further experiment was conducted to investigate the effects of this factor.

Eggs from a single female were fertilized in the laboratory by sperm from a single male. The fertilized eggs were separated into three lots and were placed in beakers of sea water. The three beakers were immersed in water in a

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[1] Contributions from the Scripps Institution of Oceanog-phy, New Series, No. 636.

### TABLE I

INFLUENCE OF LIGHT ON THE MEAN NUMBER OF VERTEBRAE IN THE GRUNION (*Leuresthes tenuis*)

| Type of illumination | Number of vertebral centra | | | Mean | Number[1] | $S(x-\bar{x})^2$ |
|---|---|---|---|---|---|---|
| | 47 | 48 | 49 | | | |
| Bright..... | 14 | 11 | .. | 47.44 | 25 | 6.16 |
| Subdued.... | 18 | 22 | .. | 47.55 | 40 | 9.89 |
| Darkness... | 52 | 157 | 2 | 47.76 | 211 | 42.16 |

[1] The original samples contained approximately identical numbers of eggs, and a good hatch was obtained with each lot. The discrepancy in numbers in the final samples is the result of mortality after hatching, during the month in which the fish were held in tanks. It is possible that the factors associated with the death of these fish were selective with respect to vertebral number.

### TABLE II

THE NUMBERS OF VERTEBRAE IN SAMPLES OF *Leuresthes tenuis* REARED IN TEMPERATURE AND SALINITY EXPERIMENTS, GROUPED ACCORDING TO THE INTENSITY OF LIGHT DURING EMBRYONIC DEVELOPMENT

| Type of illumination | Number of vertebral centra | | | | | Mean | Number | $S(x-\bar{x})^2$ |
|---|---|---|---|---|---|---|---|---|
| | 46 | 47 | 48 | 49 | 50 | | | |
| Bright...... | 11 | 119 | 65 | 1 | .. | 47.29 | 196 | 64.00 |
| Subdued.... | 8 | 160 | 184 | 12 | 1 | 47.56 | 365 | 136.10 |
| Darkness[1]... | .. | 19 | 32 | 1 | .. | 47.65 | 52 | 13.77 |

[1] Adult fish from nature. The developing eggs are buried in the sand, hence no light can reach them.

large glass aquarium in a controlled-temperature room. One beaker was painted black and was provided with an opaque cover; the second was shaded from the direct light entering the windows in daytime, and was illuminated from above by a 100-watt bulb at a distance of about five feet; the third was exposed to direct light from the windows during the day, and received the same illumination as the second beaker at night. The second and third beakers were provided with covers of transparent glass. Until hatching occurred, about ten days after fertilization, the room was maintained at an average temperature of about 24° C. No significant differences in water temperature were observed in the three beakers. Aeration was provided by a thin stream of air bubbled into each.

At hatching, the prolarvae were transferred to three aquaria of aerated standing sea water under equal conditions of temperature and light. The young fish were fed with brineshrimp nauplii (McHugh and Walker, 19
until they were about one month old. T
was necessary to ensure ossification of
vertebral columns. At this stage the yo
were killed in a five percent solution of form
buffered with borax, and after a period
hardening, the tissues were cleared and
bones stained by the KOH-Alizarin-Glyce
method.

The vertebral counts are given in Tabl
Analysis of variance of the means shows t
there is little chance that the three lots co
have been drawn from the same popula
($F = 7.85$, $F_{0.01} = 4.7$). The experim
seems to show, at a high level of statist
significance, that the mean number of ve
brae in the grunion can be modified by l
during the embryonic stages.

A large-scale experiment, planned to con
the validity of these results, unfortuna
failed due to technical difficulties, and it
not possible to repeat the experiment la
Indirect confirmation, admittedly inadequ
is afforded by the results of the previous st
ies. Although water temperatures and salini
were varied in these experiments, the m
numbers of vertebrae showed no regular va
tion with either factor. Ignoring the poss
complicating effects of these other factors,
grouping the experimental lots in broad c
gories according to the intensity of the i
dent light, the figures in Table II were obtai
Analysis of variance of these means indica
also at a high level of statistical significa
($F = 15.56$, $F_{0.01} = 4.65$), that the three c
posite samples could not have been drawn f
the same population. Furthermore, the
clusion again is reached that an inverse r
tionship exists between light intensity and
number of vertebrae produced.

It is not well understood by what mechan
light is able to affect metabolism during e
development. Heilbrunn (1943) stated
the visible light increases the cellular pe
ability of plants, but that little work has b
done along these lines on animals. He did p
out, however, that the permeability of b
cells is greater in light than in darkness.
haps by some such action, light is able to
the rate of metabolic activity, as tempera
is known to do. The production of low num
of vertebrae at high temperatures seems so
how to be related to the more rapid rat

development and differentiation occurring under such conditions, and variations in the balance between these two processes.

## LITERATURE CITED

DANNEVIG, ALF. 1932. Is the number of vertebrae in the cod influenced by light or high temperature during the early stages? *Jour. Cons., 7 (1): 53–59.*

HEILBRUNN, L. V. 1943. An outline of general physiology. *W. B. Saunders Co., Philadelphia: xii + 748.*

HEUTS, M.-J. 1946. La régulation minérale en fonction de la température chez *Gasterosteus aculeatus. Ann. Soc. Roy. Zool. Belgique, 76 (1945): 88–99.*

JOHNSEN, SIGURD. 1936. On the variation of fishes in relation to environment. (Preliminary account.) *Bergens Mus. Arbok, Naturv. Rek. (4): 1–26.*

MCHUGH, J. L., AND BOYD W. WALKER. 1948. Rearing marine fishes in the laboratory. *Calif. Fish and Game, 34 (1): 37–38.*

SCHMIDT, JOHS. 1918. Racial studies in fishes. I. Statistical investigations with *Zoarces viviparus L. Jour. Genetics, 7 (2): 105–18.*

——— 1919. Racial studies in fishes. II. Experimental investigations with *Lebistes reticulatus* (Peters) Regan. *Ibid., 8 (3): 147–53.*

——— 1920. Racial investigations. V. Experimental investigations with *Zoarces viviparus L. Compt.-Rend. Lab. Carlsberg, 14 (9): 1–14.*

——— 1921. Racial investigations. VII. Annual fluctuations of racial characters in *Zoarces viviparus L. Ibid., 14 (15): 1–24.*

TÅNING, Å. VEDEL. 1944. Experiments on meristic and other characters in fishes. I: On the influence of temperature on some meristic characters in sea trout and the fixation-period of these characters. *Medd. fra Komm. Danmarks Fisk. Havunder. Ser. Fisk., 11 (3): 1–66.*

——— 1952. Experimental study of meristic characters in fishes. *Biol. Rev., 27: 169–93.*

VLADYKOV, VADIM D. 1934. Environment and taxonomic characters of fishes. *Trans. Roy. Canadian Inst., 20: 99–140.*

WILLER, A. 1928. Untersuchungen über das Wachstum bei Fischen. II, III und IV. Weitere Untersuchungen über den Einfluss äusserer Faktoren auf das Wachstum der Bachforellenbrut. *Zeitschr. für Fischerei, 26: 565–606.*

WORTH, STEPHEN G. 1898. The shad. *In:* A manual of fish-culture . . . (prepared under the direction of John J. Brice). *App. to Rept. U. S. Comm. Fish and Fish., 23 (1897): 133–158.*

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# Reflection of Sound in the Ocean from Temperature Changes*

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When the temperature of the ocean changes with depth within a horizontal layer, it is accompanied by a change in the velocity of sound. The reflection of sound from such a transition layer depends on the incident angle and wavelength of the sound, the thickness of the layer, the manner in which the velocity changes, and the total amount of the change. The usual formula for reflection assumes a transition layer of negligible thickness. The reflection coefficient then depends only on the incident angle and the total velocity change. This case is treated and numerical values are given for the reflection coefficient under conditions of practical interest. It is then shown that for a gradual velocity change which corresponds to certain temperature data, the reflection coefficient for small glancing angles of incidence changes gradually with increasing layer thickness and may be approximated very closely by the usual formula. Quantitative comparison of the cases is made and the general applicability of the approximation is discussed.

## I. INTRODUCTION

RATHER abrupt changes in the temperature of the ocean with depth are observed.[1] These changes cause a corresponding variation in the velocity of sound, and it is of interest to inquire as to the reflection of sound from strata in which such changes occur.

The usual treatment of reflection assumes a discontinuous velocity-depth function at the interface of two media of different indices of refraction. This is certainly a good approximation to a continuous change, provided it takes place within a distance which is small compared to the wavelength of the sound. In the ocean, however, there are indications of temperature and sound velocity changes occurring over an interval of several inches. Since the wavelength of 24-kc sound used in echo-ranging is about 2.4 inches, the above approximation is no longer justified without further study.

It is therefore convenient to treat the problem of reflection in two parts according to whether the velocity change is "sharp" or "smooth." The term "sharp" will be used to indicate the case in which the layer of velocity change has negligible thickness. A "smooth" change will denote a velocity change in a layer whose thickness is not negligible. The meaning of "negligible" in this connection will be discussed below. The fraction of incident energy which is reflected in the two cases will be called the sharp and smooth reflection coefficients and designated by $r$ and $r'$, respectively. It is seen that the sharp reflection coefficient is the usual reflection coefficient associated with a discontinuous $\rho_0 c$ change ($\rho_0$ being the density and $c$ the sound velocity) and is given by the usual elementary calculation, but that the second requires a treatment which recognizes the wave nature of sound.

The analogous problem of reflection of electrons from a region in which their velocity changes (i.e., a potential barrier) has been treated by Eckart.[2] By a change of notation these results can be applied immediately to give the smooth reflection coefficient for sound, as has been shown by comparison with a paper by Epstein.[3] After a brief examination of the reflection from a sharp change, the results for the smooth case will be given and the smooth reflection coefficient $r'$ will be shown to depend in a simple way on the sharp reflection coefficient $r$, and on a parameter $u$ defined below.

## II. REFLECTION FROM A SHARP VELOCITY CHANGE

A discontinuous change in the sound velocity will be assumed at the boundary between two semi-infinite media, the velocity being $c$ in the first and $c'(=c+\Delta c)$ in the second, with $\theta$ and $\theta'$ the glancing angles of incidence and refraction (Fig. 1).

Snell's law is

$$c' \cos\theta = c \cos\theta' \tag{1}$$

for any ray, and the amplitude reflection coefficient is

$$s=\frac{c' \sin\theta - c \sin\theta'}{c' \sin\theta + c \sin\theta'}, \tag{2}$$

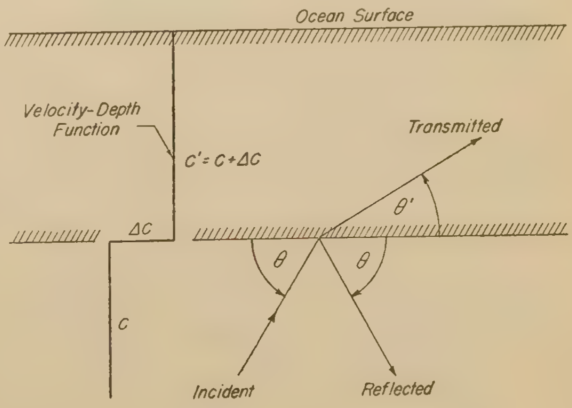

FIG. 1. Sound at a sharp velocity change.

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* This work was performed in 1943 while the author was on the staff of the University of California Division of War Research, supported by OSRD under Contract OEMsr-30, and by the Bureau of Ships, Navy Department under Contract NObs 2074. Contribution from the Scripps Institution of Oceanography, New Series, No. 637.

[1] *Principles of Underwater Sound*, NDRC Summary Technical Reports, Chapter 2, Fig. 5, p. 12.

[2] Carl Eckart, Phys. Rev. **35**, 1303–1309 (1930).

[3] Paul S. Epstein, "Effect of the Thermocline on the Propagation of Sound," UCDWR, No. 5 (March 19, 1942).

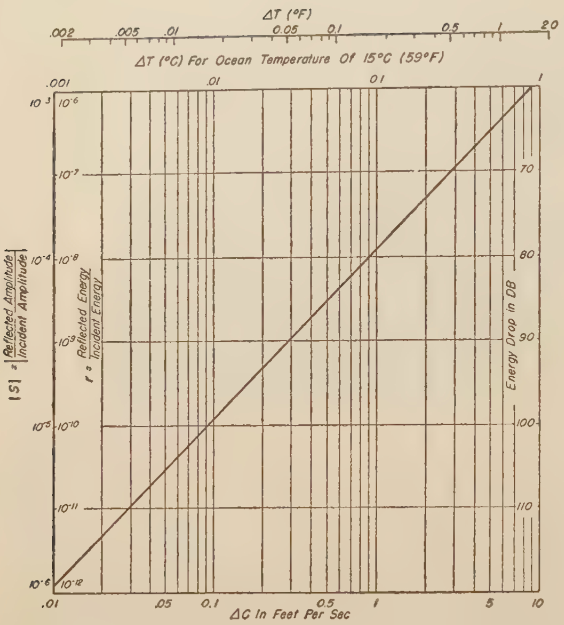


FIG. 2. Fraction of energy reflected at normal incidence from a sharp velocity change (increase or decrease) of $\Delta c$.

provided the densities of the two media are assumed to be equal, a justifiable approximation in considering the ocean. The sign of $s$ is the same as that of $\Delta c$ (i.e., positive for an increase in sound velocity along the incident ray and negative for a decrease). To a sufficient approximation, the energy reflection coefficient is $r=s^2$. Replacing $c'$ by $c+\Delta c$ and assuming normal incidence ($\theta=\theta'=90°$), Eq. (2) reduces to $s=\Delta c/2c$ and the energy reflection coefficient becomes

$$r=(\Delta c/2c)^2 \qquad (3)$$

for normal incidence and is plotted in Fig. 2. T corresponding temperature change $\Delta T$ is also shov and the reflected energy is seen to be down 60 or 80 for ordinary values of $\Delta T$.

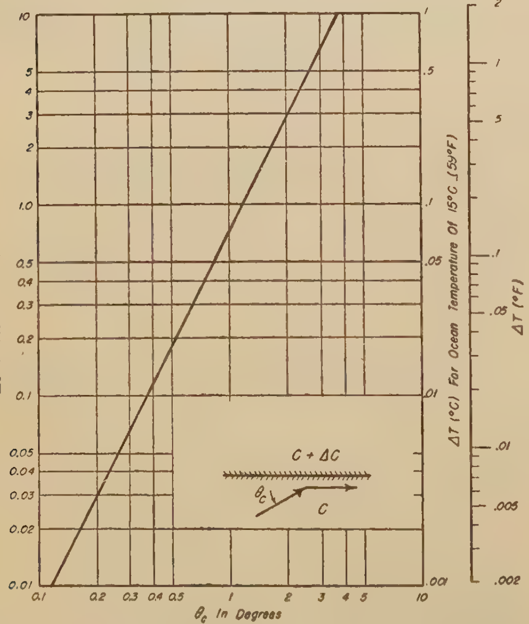


FIG. 3. Critical angle $\theta_c$ for various values of $\Delta c$ and $\Delta T$.

It is convenient to give the following formulas terms of radians rather than degrees. For small values $\theta$, Eq. (1) becomes approximately

$$\theta'=[\theta^2-(2\Delta c/c)]^{\frac{1}{2}},$$

and the critical angle is given by $\theta'=0$ or

$$\theta_c=(2\Delta c/c)^{\frac{1}{2}},$$

which is shown in Fig. 3. Using Eq. (4), the angle refraction $\theta'$ may be conveniently written

$$\theta'^2=\theta^2-\theta_c^2$$

and is plotted in Fig. 4. The value of the reflect

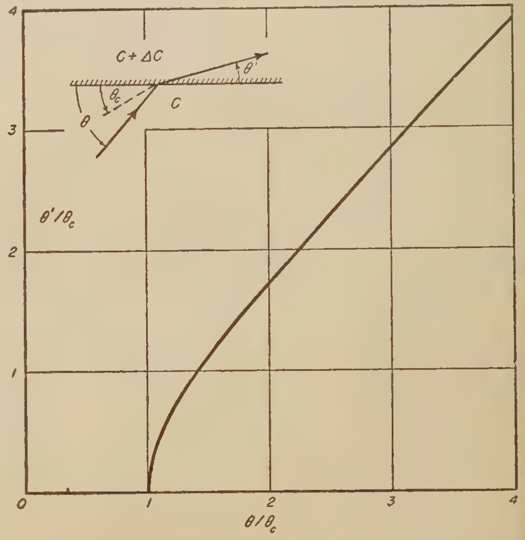


FIG. 4. Relation between incident, refracted, and critical an

coefficient is then approximately

$$r=(\theta-\theta')^2/(\theta+\theta')^2$$

for small glancing angles.

The curves in Figs. 5 and 6 show how $r$ changes the angle $\theta$ for various values of $\Delta c$. Figure 5 is dr for a velocity increase. For a given $\Delta c$, it is seen for $\theta$ less than the critical angle the reflection is perf Within several degrees of the critical angle the refle energy drops off rapidly to very small values. In F the reflection takes place at a velocity decrease, there is no critical angle. The reflection is perfect at grazing incidence ($\theta=0°$) and drops rapidly to s values (1 percent or less) as the glancing angle incre to 4° or 5°.

It should be mentioned that the reciprocity theo holds; i.e., the reflection coefficient is independen the direction of propagation along a given path. T suppose sound from below to be incident on a stra t an angle of 3° with the horizontal, with the transitted ray emerging above at 4°, then the theorem ates that the reflected energy will be the same action of the incident energy as if the sound were cident from above at 4°, with the transmitted sound merging below at 3°.

It may be concluded that good reflection from strata ith sharp temperature changes occurs only when the y angle with the horizontal is very near the grazing ngle on the high velocity side and less than or equal to e critical angle on the low velocity side.

## III. REFLECTION FROM A SMOOTH VELOCITY CHANGE

In general, it may be assumed that the velocity of ound changes somewhat as shown at the left of Fig. 7.

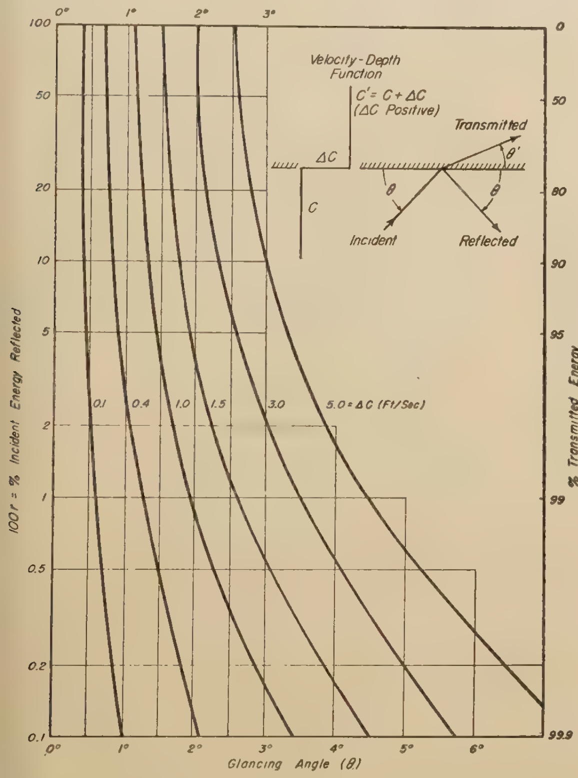


FIG. 5. Percent reflected energy from sharp velocity increase.

ound of a single frequency rises from $z=-\infty$ through e layer of velocity change $v(z)$ (whose thickness is $2d$) wards the surface and $z=+\infty$. The velocity-depth nction shown is given by

$$v^{-2}=(c+\Delta c)^{-2}+2\Delta c\{c^3[1+\exp(2\pi z/d)]\}^{-1}. \quad (6)$$

he coordinate $z$ is measured upward from the center of e layer. Outside this layer the velocity approaches e limiting values $c$ and $c'(=c+\Delta c)$ very rapidly. The tuation, therefore, approximates the assumption of latively constant velocity in each of two semi-infinite edia which are separated by a stratum of changing ound velocity.

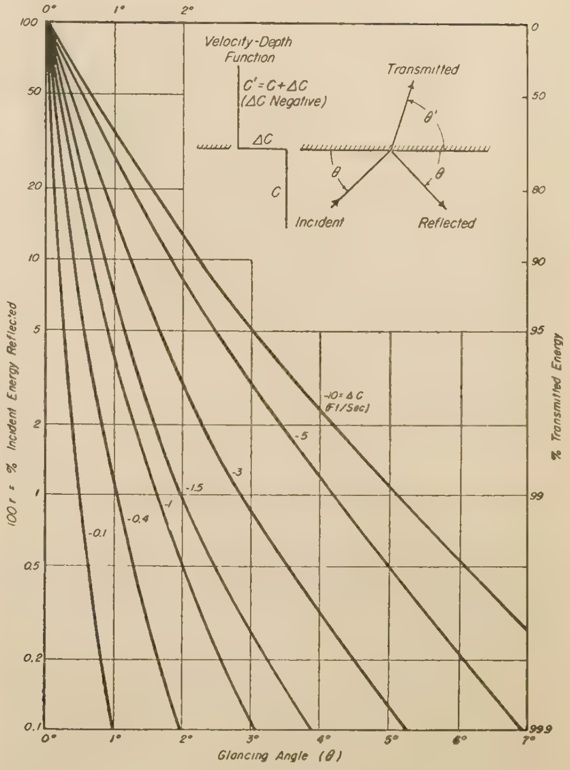


FIG. 6. Percent reflected energy from sharp velocity decrease.

The smooth amplitude reflection coefficient $s'$ is then a function of the sharp reflection coefficient $s$ (associated with the same $\Delta c$ and $\theta$) and of the variable

$$u=(2\pi d/\lambda)\sin\theta,$$

$\lambda$ being the wavelength of the sound. (The differences in wavelength in the two media may be ignored for present purposes.) The energy reflection coefficients are then

$$r=s^2 \quad \text{and} \quad r'=s'^2. \quad (7)$$

With these definitions

$$s'=\sinh[us/(1+s)]/\sinh[u/(1+s)], \quad (8)$$

and has the same sign as $s$.

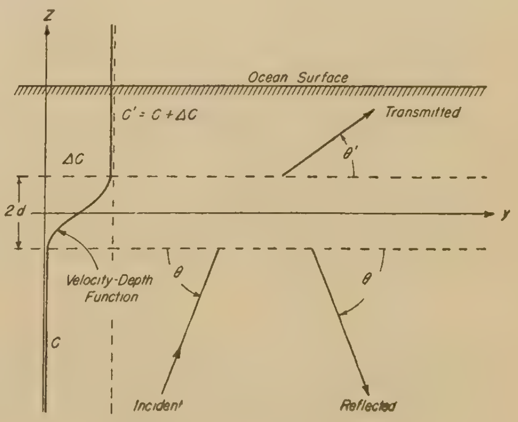


FIG. 7. Sound at a smooth velocity change.

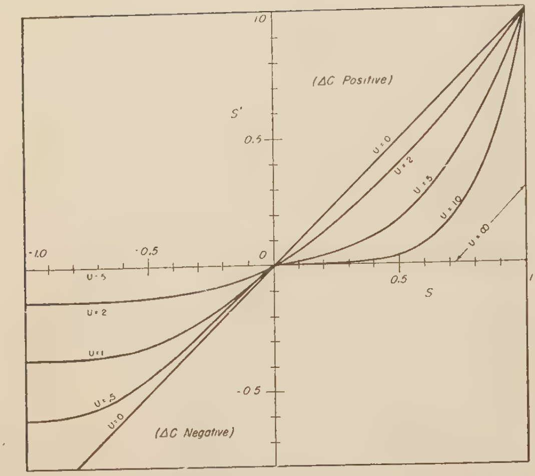


Fig. 8. Sharp and smooth amplitude reflection coefficients.

Figure 8 is a graphic presentation of Eq. (8), showing $s'$ as a function of $s$ for various values of $u$. All of the curves pass through the origin, and $s'=1$ corresponds to $s=1$ for all values of $u$. In general, an increase in $u$ produces a decrease in $s'$, this decrease being markedly greater for negative values of $s$ than for positive values. This asymmetry does not imply a departure from the reciprocity principle, since the value of $u$ is partially determined by the angle of incidence, but is independent of the angle of refraction.

In Fig. 9, $r'$ is shown at a velocity increase for two values of $2d/\lambda$ (the layer thickness in wavelengths), with curves for the sharp reflection coefficient ($r$) repeated from Fig. 5 for comparison. Figure 10 shows the corresponding $r'$ and $r$ curves for a velocity decrease.

The variable $u$ has a simple significance. If $A$ is a point at the center of the transition layer and $B$ a point vertically above (or below) $A$ at the distance $d$, then $u$ is the phase difference (in radians) of the sound wave at $A$ and at $B$. Hence, the layer can be considered as an abrupt change whenever this phase difference is small, but it must be treated as a smooth change when this difference is large.

It will be seen that when $s=+1$, corresponding to perfect reflection at a sharp velocity increase, the sinh arguments become equal in Eq. (8), giving a smooth reflection coefficient of one. At a sharp velocity decrease the reflection is perfect ($s=-1$) at grazing incidence ($\theta=0$), making $u=0$ and again giving a smooth reflection coefficient of one. Thus, whenever the sharp reflection becomes perfect the smooth reflection also becomes perfect. Two results are thus reached for the smooth velocity change:

1. At grazing incidence the reflection is perfect.
2. At any velocity increase ($\Delta c$) of the form of Eq. (6), there will exist a critical angle which is identical with the critical angle associated with an equal discontinuous velocity change.

It can be shown that if a ray has a smaller glanci angle of incidence than this critical value, it will have vertex within the stratum of change and the ray w curve back. The existence of a critical angle for reflecti at a smooth velocity change is therefore consistent wi refraction theory.

The calculation of $r'$ is simplified by using the vario graphs given above. From Fig. 3, the value of $\theta_c$ ca be obtained for a given $\Delta T$ or $\Delta c$. Figure 4 simplifi the calculation of $\theta'$ from $\theta$ and $\theta_c$, whereupon

$$s=(\theta-\theta')/(\theta+\theta'). \qquad ($$

Knowing the value of $u$ and $s$, $s'$ can be obtained fro Fig. 8. The accuracy thus obtained is sufficient f most purposes, except when $s$ is very small. In this ca Eq. (8) reduces to

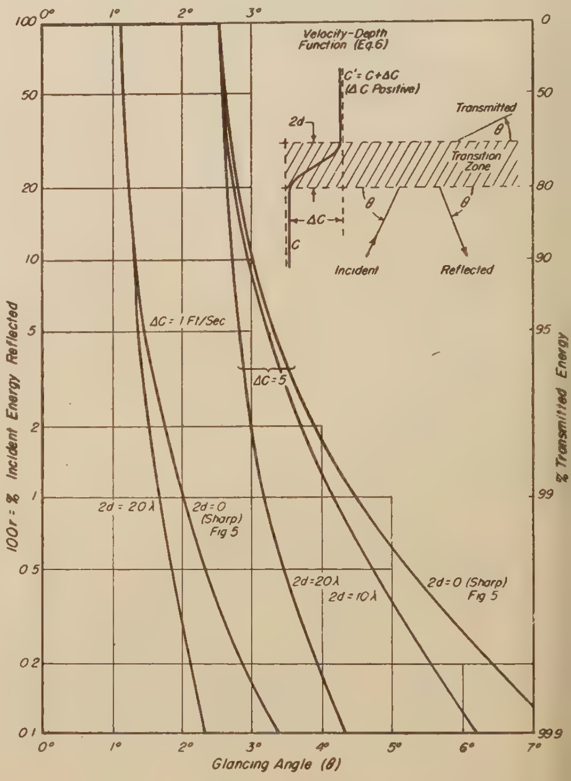


Fig. 9. Percent reflected energy from smooth velocity increas

$$s'=us/\sinh u. \qquad (1$$

The function $u/\sinh u$ decreases very rapidly wi increasing $u$, and is given in Table I. It is seen that and $s$ have the same order of magnitude only for sm values of $u$.

## IV. APPLICATION AND GENERALITY OF RESULT

The glancing angles usually encountered in ec ranging are less than 5°; small values of $\theta$ are therefo of primary interest. It can be seen at once from Figs. 6, 9, and 10 that the reflection for such angles may far from negligible.

### Reflection from a Single Layer

To illustrate the magnitude of the smooth reflection from a single layer, two typical examples involving upward and downward refraction were calculated (Figs. 11 and 12).

In Example 1 the projector is in an isothermal layer extending from the surface to a depth of 50 ft. Owing to pressure the velocity increases with depth in this layer, being 0.9 ft/sec greater at 50 ft than at the surface and giving rise to mild upward refraction of the sound field. The various rays are incident upon a layer in which the velocity decreases according to Eq. (6). The reflection coefficient for 24-kc sound is calculated for several layer thicknesses and for two values of $\Delta c$ (−10 t/sec and −1 ft/sec) corresponding to a temperature decrease of about 2°F and 0.2°F, respectively. An sovelocity layer lies below the reflecting layer. The eflection coefficient increases with range from very low values at short ranges until it reaches one for the ray which is tangent to the top of the reflecting layer at D (Fig. 11).

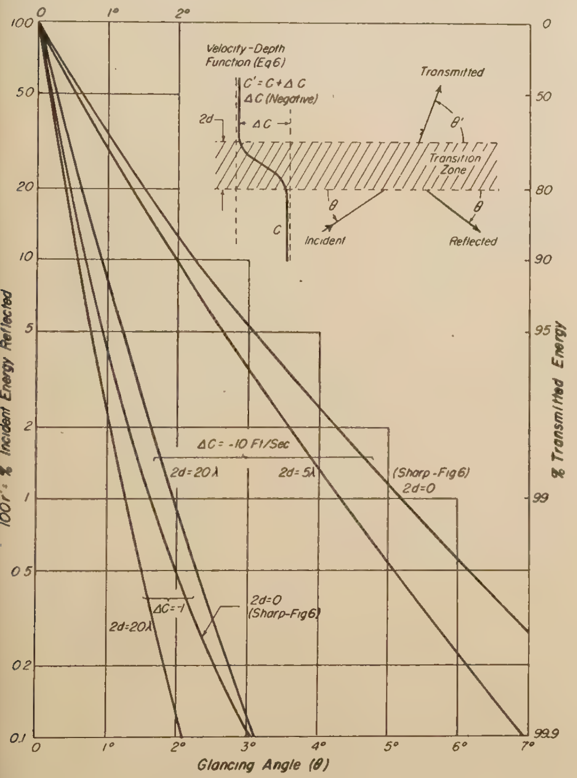


Fig. 10. Percent reflected energy from smooth velocity decrease.

In the second example (Fig. 12) a negative velocity gradient causes downward refraction in the top layer nd, at a depth of 30 ft, the sound (again 24 kc) is eflected from the layer of change. The same values of $\Delta c$ and $2d$ were used. Here it will be seen that the best eflection occurs at $B$ for sound traveling along the xial ray (which leaves the projector horizontally), since this ray has the smallest glancing angle of incidence. Beyond the point $B$, the reflection drops off with increasing range until it reaches a small value at $D$ for the limiting ray which is tangent to the surface. Inside the axial ray the reflection decreases more rapidly and drops to extremely small values for short ranges.

In general the reflection will be greater for upward refraction than for downward refraction and also greater at a velocity increase than at a velocity decrease as assumed in the two examples. It should also be remembered that the same reflection coefficient will again act on a returning echo from a target below the reflecting layer, so that the echo intensity will be lowered by a factor of $(1-r')^2$ from the value to be expected if the reflection is ignored.

### Reflection from Many Layers

If the velocity depth curve is a series of steps randomly spaced and consisting of $n$ alternate high and low gradient layers, the reflection coefficient is $\rho$, where

$$\rho/(1-\rho)=\sum_{k=1}^{n} r_k/(1-r_k), \tag{11}$$

$r_k$ being the reflection coefficient at the top of the $k$th layer. If $r_k$ is small compared to one, Eq. (11) becomes approximately

$$\rho=\sum_{k=1}^{n} r_k. \tag{12}$$

As the sound traverses the layers, the glancing angle of incidence increases and the reflection coefficient decreases rapidly. In general, therefore, only the first few layers need be considered in summing Eq. (12).

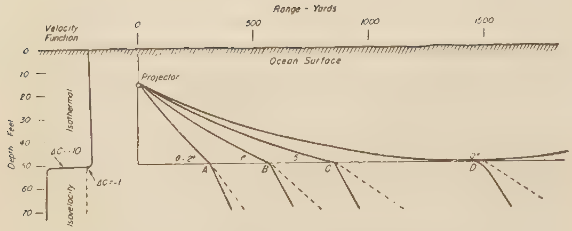
### Generality of Results

In Fig. 13 three velocity-depth functions are shown:

1. The first ("exponential") is the form given by Eq. (6), used in calculating the smooth reflection coefficient.
2. The second ("observed") has the form indicated by certain temperature data.
3. The third ("hyperbolic") is a more gradual change than either of the others.

Table I. Values of $u/\sinh u$.

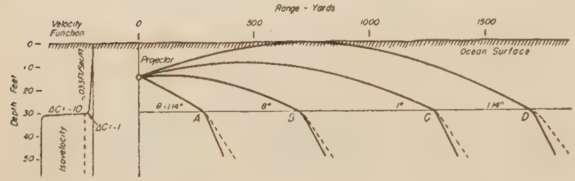
| $u$ | $u/\sinh u$ |
|---|---|
| 0.0 | 1.0 |
| 1.0 | 0.85 |
| 2.0 | 0.55 |
| 3.0 | 0.30 |
| 4.0 | 0.15 |
| 5.0 | 0.067 |
| 7.0 | 0.013 |
| 10.0 | 0.001 |



SMOOTH REFLECTION COEFFICIENT (r′)

| | A | B | C | D |
|---|---|---|---|---|
| ΔC = -10 Ft/Sec 2d = 1 Ft | 0.10 | 0.32 | 0.55 | 1.0 |
| ΔC = -10 Ft/Sec 2d = 5 Ft | 0.0035 | 0.059 | 0.24 | 1.0 |
| ΔC = -10 Ft/Sec 2d = 10 Ft | 0.000016 | 0.0035 | 0.063 | 1.0 |
| ΔC = -1 Ft Sec 2d = 1 Ft | 0.005 | 0.042 | 0.20 | 1.0 |

FIG. 11. Example 1—Reflection with upward refraction for 24-kc sound.



SMOOTH REFLECTION COEFFICIENT (r′)

| | A | B | C | D |
|---|---|---|---|---|
| ΔC = -10 Ft/Sec 2d = 1 Ft | 0.25 | 0.40 | 0.32 | 0.25 |
| ΔC = -10 Ft/Sec 2d = 5 Ft | 0.040 | 0.11 | 0.059 | 0.040 |
| ΔC = -10 Ft/Sec 2d = 10 Ft | 0.0015 | 0.011 | 0.0035 | 0.0015 |
| ΔC = -1 Ft/Sec 2d = 1 Ft | 0.025 | 0.072 | 0.042 | 0.025 |

FIG. 12. Example 2—Reflection with downward refraction for 24-kc sound.

The main difference in the first and last forms lies in their asymptotic approach to the constant values $c$ and $c'$. The first is exponential, and the third is approximately hyperbolic in form. There are theoretical reasons for believing that the latter is much less effective in reflection. However, it is evident that the exponential is the better approximation to the observed form, since the data indicate an abrupt rather than a gradual change from low to high gradient. It is, therefore, reasonable to believe that the calculated reflection from the assumed exponential is a conservative estimate of reflection to be expected from the observed change.

## V. CONCLUSIONS

The principal results may be summarized as follows:

1. For normal incidence the reflection is very small and depends only on the total velocity change. It is independent of whether the velocity is increasing or decreasing. For a layer thickness up to a third of a wavelength the reflected energy is 60 db below the incident energy for a velocity change of 10 ft/sec (corresponding to a temperature change of about 1°C); it is 80 db down for 1 ft/sec (0.1°C) and 100 db for 0.1 ft/sec (0.01°C). The reflection then drops very rapidly with increasing thickness, being about one-te the values above for a thickness of one wavelen and about one-hundredth for a thickness of t wavelengths.

2. When the incident sound encounters a veloc decrease the reflection becomes perfect as the glanc angle of incidence decreases to zero. The reflect drops very sharply for increasing glancing angle.

3. At a velocity increase the familiar critical an exists, and its value depends only on the total veloc change, not on the wavelength or layer thickn For glancing angles less than the critical angle (whic of the order of 1° for commonly found temperat changes), the reflection is perfect, regardless of wa length and layer thickness. As the glancing an increases a degree or two above the critical valu the reflection drops very sharply (from 100 percent 1 percent).

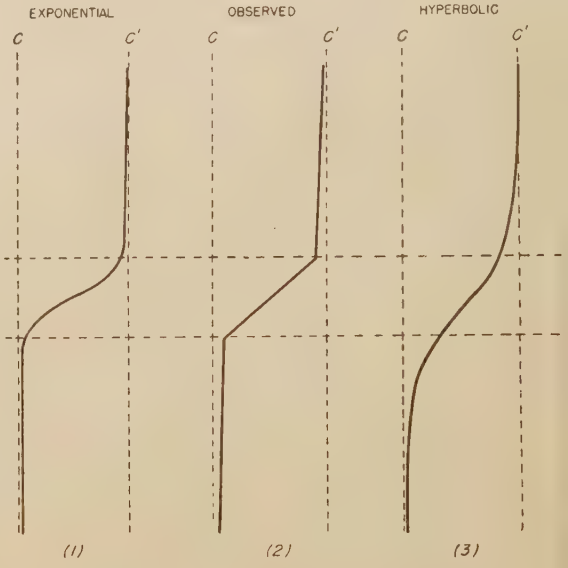


FIG. 13. Various velocity depth functions.

4. In general, for either of the above cases, the ref tion drops off gradually with decrease in wavelen and increase in layer thickness.

5. In general, a velocity change can be conside as abrupt whenever the phase difference of the sou at two points vertically above each other and opposite sides of the layer is less than one radian formula is given which is valid when this phase ference is greater than one radian.

6. In echo-ranging with 24-kc sound, changes temperature occurring in horizontal layers less t 4 ft thick may usually be treated as abrupt since sound rays generally approach the layers at sm glancing angles of incidence.

INMAN, DOUGLAS L. Areal and seasonal variation in beach and nearshore sediments at La Jolla, California. Tech. Memor. U.S. Army Eros. Bd., no. 39, pp. 1-82, 1953. (Unavailable for exchange.)

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# Relation between Time Averages and Ensemble Averages in the Statistical Dynamics of Continuous Media

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The method of correlations, which has been widely used in the theory of turbulence, is applied to the case of a field that satisfies linear equations. It is found that most of the difficulties encountered in the theory of turbulence disappear when the equations are linear and that a number of general results can be obtained.

In particular, it is possible to use an analog of Gibbs' procedure of replacing a time average by an ensemble average. The mathematical foundations of this procedure are discussed and shown to be considerably different than for dynamical systems with a finite number of degrees of freedom, to which the method is usually applied. In particular, it is shown that it can be applied to dissipative fields excited by a randomly varying force.

Three examples are treated in some detail: statistically uniform but nonisotropic fields; statistically nonuniform, dissipative fields excited by a random force; and the scattering of monochromatic radiation by inhomogeneities of the refractive index.

The method of ensembles, as applied to these problems, appears to have a mathematical foundation that is rather simpler than in other cases that have been considered in the past, but several basic and unsolved problems are mentioned.

## I. INTRODUCTION

THE methods of classical statistical mechanics were developed primarily to deal with the thermodynamic equilibrium of systems with a finite number of degrees of freedom. They have been extended to the case of continuous media, but only by the device of supposing a portion of the medium to be enclosed by ideal, perfectly reflecting boundaries. They have also been extended to include small departures from thermodynamic equilibrium, but in the case of continua, no methods similar to those of kinetic theory or general statistics have been developed. The existing methods are better adapted to calculating the constant properties of the medium than the statistical determination of its more complicated modes of motion.

Other methods have been introduced into the theory of turbulence, which do not require that the system be n thermodynamic equilibrium. These methods consist largely in the study of the correlation of two quantities when measured at different points in space and time.[1–4] Since the interest has centered on hydrodynamic problems, governed by nonlinear equations, progress has been difficult, and hampered by the fact that the equations for the double correlation $\langle uv\rangle$ also contain the triple correlation $\langle uvw\rangle$, etc.[1] Attention has been centered on this difficulty[†] and the search for valid hypotheses to enable it to be circumvented. As a result, only more or less conventional solutions have been obtained, and problems involving boundary conditions or driving forces have been ignored.

When the same methods are applied to electrodynamic[5] or acoustic[6] problems, the difficulty vanishes, and other problems claim the attention. These are of two kinds: the one has already been indicated, and involves boundary conditions and driving forces. In principle, these present no difficulty and it is merely a matter of arranging the calculations systematically. This is the primary topic of the following paper.

The second kind of problem is more fundamental. It has been customary in the theory of turbulence, to consider the averages to be temporal, rather than ensemble averages (see reference 1). This is an attractive approach, but can be expected to encounter all of the difficulties inherent in the ergodic theorem. However, these expected difficulties do not obtrude themselves at once, and the ensemble average appears in the calculation merely as a convenient device for the solution of the differential equations obeyed by the temporal averages (see Sec. III, below). It is only when one endeavors to generalize this method of solution that the expected difficulties arise (Sec. IX, below).

Let $p(\mathbf{x}t)$ be any field that obeys the equation

$$Lp=\partial p/\partial t, \tag{1}$$

$L$ being a linear operator that commutes with $t$ and $\partial/\partial t$, and such that the eigenvalue problem

$$Lf=-i\omega f \tag{2}$$

has no discrete eigenvalues. This implies that any boundary conditions are included in the operator $L$, but that they are not stringent, as are for example, those of a cavity with perfectly reflecting walls. If $L$ contains no frictional terms, the boundary conditions must be such that energy can be dissipated by radiation to infinity, and may include the condition for "outgoing waves" (see Sec. VIII). In dealing with problems such as this, it has been customary to introduce additional, artificial boundary conditions, until the spectrum of Eq. (2) becomes a line spectrum and the system can be considered closed. At the end of all other calculations, these artificial boundary conditions are removed, which is a difficult limiting process.

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* On leave from the Scripps Institution of Oceanography, La Jolla, California.

[1] See references 2, 3, 4, or the review of J. E. Moyal, *Stochastic Processes and Statistical Physics*, J. Roy. Stat. Soc. **B11**, 150 (1949).

[2] O. Reynolds, Trans. Roy. Soc. (London) **186** (1895).

[3] G. I. Taylor, Proc. London Math. Soc. **20**, 196 (1922).

[4] T. v. Kármán and L. Howarth, Proc. Roy. Soc. (London) **A174**, 192 (1938).

[†] This difficulty is more obvious than serious, as will be shown n a subsequent paper.

[5] C. L. Pekeris, Proc. Intern. Congr. Math. **1**, 648 (1950).

[6] C. Eckart, J. Acoust. Soc. Am. **25**, 195 (1953).

There are also reasons for doubting the validity of these procedures. The statistical mechanics of closed systems has been developed with special reference to thermodynamic equilibrium, and its postulates are not certain to be applicable under other conditions. To emphasize the lack of equilibrium, a "driving force" will be added to Eq. (1), so that it becomes

$$Lp=\partial p/\partial t+a(\mathbf{x}t), \tag{1.1}$$

the function $a$ being given as part of the data of the problem.

The usual method of solving such problems is to expand both $p$ and $a$ as Fourier integrals. This implies that the time averages of $p^2$ and $a^2$ are zero. This is not permissible if one wishes to deal with statistically steady states, for which these and other time averages are finite. The objective of the following paper will be to develop methods for calculating such averages without solving the more difficult problem of finding an analytic expression for the solution that is being averaged. This is essentially the basic idea of the Reynolds[2] and v. Kármán[4] approach to problems of turbulence.

## II. CONVOLUTION AND CORRELATION

In the following, much use will be made of the two limiting processes,[7]

$$\{f(\mathbf{x},t)\}=\lim_{T\to\infty}\int_{-T}^{T}f(\mathbf{x},t)dt \tag{3}$$

and

$$\langle f(\mathbf{x},t)\rangle=\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}f(\mathbf{x},t)dt. \tag{4}$$

With their aid, one may define the convolution of two fields $f(\mathbf{x},t)$ and $g(\mathbf{x},t)$ as

$$\{fg'\,|\,\tau\}=\{f(\mathbf{x},t)g(\mathbf{x}',t-\tau)\}, \tag{5}$$

and the correlation as

$$\langle fg'\,|\,\tau\rangle=\langle f(\mathbf{x},t)g(\mathbf{x}',t-\tau)\rangle. \tag{6}$$

It is important to note that both the convolution and the correlation depend on the two points $\mathbf{x}$ and $\mathbf{x}'$ in space, as well as on the delay time $\tau$. If the fields $f$ and $g$ each have $n$ components, the symbols here defined have $n^2$ components; they are fields in the seven-dimensional space $\mathbf{x}$, $\mathbf{x}'$, $\tau$.

If $p$ is a solution of Eq. (1.1) for a given $a$, anc both can be expressed as ordinary Fourier integrals the time, then the convolutions $\{aa'|\tau\}$, $\{pa'|$ $\{pp'|\tau\}$ will be finite and the corresponding correlatic will be zero. Such solutions will be called Class $I$ ($I$ integrable). If both $p$ and $a$ can be expressed as Fourier (or similar but more general trigonometr series, the correlations will be similar series in delay time $\tau$, while the integrals defining the convo tions will diverge. Such solutions will be called Class (averageable, line spectrum). There will certainly other solutions for which the correlations are fin but which do not have pure line spectra; these will called Class $AC$.

It is this Class $AC$ that contains the solutions t are of interest in statistical mechanics. There are simple general methods for representing them a lytically, nor is it necessary to find such metho It is typical of statistical mechanics that its object is the calculation of averages (including correlatio rather than the determination of detailed depende on time and space.

In the present case, this is relatively simple, for correlations satisfy a set of linear equations that readily deriveable from Eq. (1.1). It is also import to note that the convolutions satisfy exactly the sa set of equations. Let

$$\begin{aligned}P&=\{pp'|\tau\}\quad\text{or}\quad\langle pp'|\tau\rangle,\\ Q&=\{ap'|\tau\}\quad\text{or}\quad\langle ap'|\tau\rangle,\\ Q'&=\{pa'|\tau\}\quad\text{or}\quad\langle pa'|\tau\rangle,\\ A&=\{aa'|\tau\}\quad\text{or}\quad\langle aa'|\tau\rangle.\end{aligned}$$

Then, ignoring any difficulties that may arise in c nection with such equations as

$$L\langle pp'|\tau\rangle=\langle(Lp)p'|\tau\rangle,$$

it is found that these fields are governed by the eq tions

$$\begin{aligned}LP&=+\partial P/\partial\tau+Q,\\ L'P&=-\partial P/\partial\tau+Q',\\ L'Q&=-\partial Q/\partial\tau+A,\\ LQ'&=+\partial Q/\partial\tau+A,\end{aligned}$$

the operator $L$ acting on $\mathbf{x}$, $L'$ on $\mathbf{x}'$. Because the o ator $L$ includes boundary conditions, these equati are more elaborate than this formal notation indica and moreover they are not the only conditions to satisfied. From Eqs. (5) and (6) it follows that

$$\{fg'|\tau\}=\{g'f|-\tau\},\quad\langle fg'|\tau\rangle=\langle g'f|-\tau\rangle,$$

so that the following symmetry conditions are requi

$$\begin{aligned}P(\mathbf{x},\mathbf{x}',\tau)&=P(\mathbf{x}',\mathbf{x},-\tau),\\ Q(\mathbf{x},\mathbf{x}',\tau)&=Q'(\mathbf{x},\mathbf{x}',-\tau),\\ A(\mathbf{x},\mathbf{x}',\tau)&=A(\mathbf{x}',\mathbf{x},-\tau).\end{aligned}$$

---

[7] In symbols such as $\{f(\mathbf{x},t)\}$, $t$ is a bound variable, while $\mathbf{x}$ is free; $\{\cdots\}$ is a definite integral over $t$, and $\langle\cdots\rangle$ is very similar.

It is both natural and convenient to suppose that all ese functions are real. Then it follows from Eqs. (3) nd (4) that

$$\{[f+\theta g']^2\}\geqslant 0, \quad \langle[f+\theta g']^2\rangle\geqslant 0, \tag{10}$$

or all real values of $\theta$. From this, it is seen that the chwarzian inequalities

$$\begin{aligned} &P(\mathbf{x},\mathbf{x},0)+2\theta P(\mathbf{x},\mathbf{x}',\tau)+\theta^2 P(\mathbf{x}',\mathbf{x}',0)\geqslant 0,\\ &P(\mathbf{x},\mathbf{x},0)+2\theta Q'(\mathbf{x},\mathbf{x}',\tau)+\theta^2 A(\mathbf{x}',\mathbf{x}',0)\geqslant 0,\\ &A(\mathbf{x},\mathbf{x},0)+2\theta A(\mathbf{x},\mathbf{x}',\tau)+\theta^2 A(\mathbf{x}',\mathbf{x}',0)\geqslant 0, \end{aligned} \tag{8.2}$$

re also required of the $P$, $Q$, and $A$ fields. If $\langle a\rangle\neq 0$, $\rangle\neq 0$, there are additional inequalities to be condered; however, it is no loss of generality to suppose at $\langle a\rangle=\langle p\rangle=0$, because the Eq. (1.1) is linear, and is can always be brought about by subtracting a onstant from the quantities concerned. This is a funamental point in the following calculations, for the equalities that involve $\langle p\rangle$ are not satisfied by $\{p\}$, in eneral. Thus the formal identity of the equations for onvolutions and correlations depends on the eliminaon of the linear averages in this way.

While these many equations and inequalities are omplicated, it will be seen that their solution is quite mple. Moreover, it will be possible to obtain solutions at cannot be either the convolution of a Class *I* lution of Eq. (1.1), nor yet the correlation of a Class *L* solution. It does not follow that they are the corretion of a Class *AC* solution, but there is a strong resumption to this effect.

## III. SOLUTION OF THE STATISTICAL EQUATIONS

Since the Eqs. (8) to (8.2) are all linear, their solutions ill conform to a limited principle of superposition, the mitation arising from the fact that the Schwarzian equalities are present. Let $P_1$, $Q_1$, $Q_1'$, $A_1$, and $P_2$, $_2$, $Q_2'$, $A_2$, be two solutions; then $P=c_1P_1+c_2P_2\cdots A$ $=c_1A_1+c_2A_2$ will again be a solution if $c_1$ and $c_2$ are oth real positive numbers. If both $c_1$ and $c_2$ are negave, $P\cdots A$ will certainly not be a solution; if one is ositive, the other negative, $P\cdots A$ may or may not be solution.

This may be generalized: if $P_q\cdots A_q$ is a family of lutions of Eqs. (8) to (8.2), $q$ being a parameter or arameters, and $w(q)$ is any non-negative function of $q$, ch that the integrals

$$P=\int w(q)P_q dq, \quad A=\int w(q)A_q dq, \tag{11}$$

onverge well, these integrals will again be a solution. ow, let $p_q$, $a_q$ be a family of Class *I* solutions of Eq. .1); their convolutions may then be substituted for $\cdots A_q$ in Eq. (11), leading to

$$=\int w(q)\{q_q p_q'|\tau\}dq, \quad A=\int w(q)\{a_q a_q'|\tau\}dq. \tag{12}$$

Since the techniques for constructing Class *I* solutions are well-known, the Eq. (12) provides a relatively simple and systematic method of solving the Eqs. (8) to (8.2).

In the next section, it will be shown that the functions defined by Eq. (12) cannot always be the convolution of any Class *I* solution, etc.; this is not, as has been remarked, proof that they are then the correlation of a Class *AC* solution $p$, but if this is the case (as one may be inclined to believe) then

$$\langle pp'|\tau\rangle=\int w(q)\{p_q p_q'|\tau\}dq, \text{ etc.} \tag{12.1}$$

The operation of forming the time average is thus replaced by the integration over $q$ and $t$; this is analogous to Gibbs' ensemble average, and for that reason, a family of Class *I* solutions with an associated weight function will briefly be called an ensemble.

The weight function here appears as an arbitrary function introduced in solving the statistical equations. In general, it will be uniquely determined in specifying the function $A=\langle aa'|\tau\rangle$. This function is appropriately considered as part of the data of the statistical problem. In the case of homogeneous problems, $A=0$ and other data must be included in the formulation of the problem in order that it have a unique solution: i.e., in order that $w(q)$ be determinate.

## IV. MATHEMATICAL PROPERTIES OF CORRELATIONS AND CONVOLUTIONS

If $a(\mathbf{x}, t)$ is a real function such that $\{aa'|\tau\}$ exists, it can be shown that $a$ has a Fourier transform $\alpha$,

$$a(\mathbf{x},t)=\int\alpha(\mathbf{x},\omega)\exp(-i\omega t)d\omega \tag{13}$$

and that

$$\alpha(\mathbf{x},\omega)=\alpha^*(\mathbf{x},-\omega), \tag{13.1}$$

while (by the Parseval theorem)

$$\{aa'|\tau\}=2\pi\int\alpha(\mathbf{x},\omega)\alpha^*(\mathbf{x}',\omega)\exp(-i\omega\tau)d\omega. \tag{14}$$

The converse of this proposition is not as simple: let $A(\mathbf{x}, \mathbf{x}', \tau)$ be a real function of the seven variables indicated, having the symmetry

$$A(\mathbf{x},\mathbf{x}',\tau)=A(\mathbf{x}',\mathbf{x},-\tau) \tag{15}$$

and satisfying the Schwarzian inequality

$$A(\mathbf{x},\mathbf{x},0)+2\theta A(\mathbf{x},\mathbf{x}',\tau)+\theta^2 A(\mathbf{x}',\mathbf{x}',0)\geqslant 0; \tag{16}$$

moreover, let

$$A(\mathbf{x},\mathbf{x}',\tau)=\int B(\mathbf{x},\mathbf{x}',\omega)\exp(-i\omega\tau)d\omega. \tag{17}$$

Then, because of the reality and symmetry of $A$,

$$B(\mathbf{x},\mathbf{x}',\omega)=B^*(\mathbf{x},\mathbf{x}',-\omega)=B^*(\mathbf{x}',\mathbf{x},\omega); \tag{18}$$

because of the second of these equations, the integral equation,

$$B(\omega)f(\mathbf{x},\omega)=\int B(\mathbf{x},\mathbf{x}',\omega)f(\mathbf{x}',\omega)d\mathbf{x}', \tag{19}$$

will have only real eigenvalues, $B(\omega)$.

If $A=\{aa'|\tau\}$, it will satisfy Eqs. (15) to (18) inclusive, and Eq. (19) will have exactly one eigenvalue

$$B(\omega)=2\pi\int|\alpha(\mathbf{x},\omega)|^2d\mathbf{x},$$

which is positive, and has the single eigenfunction $\alpha(\mathbf{x},\omega)$ associated to it. Conversely, if Eq. (19) has just one, positive and nondegenerate, eigenvalue, and if $f(\mathbf{x},\omega)$ is the normalized eigenfunction, then

$$B(\mathbf{x},\mathbf{x}',\omega)=B(\omega)f(\mathbf{x},\omega)f^*(\mathbf{x}',\omega) \tag{20}$$

and the function

$$\alpha(\mathbf{x},\omega)=[B(\omega)/2\pi]^{\frac{1}{2}}f(\mathbf{x},\omega) \tag{20.1}$$

will have the symmetry of Eq. (13.1). If, when this function is substituted into Eq. (13) the integral converges, the function $A$ will be the convolution of the resulting function $a$.

Next, let the function $A$ be defined in terms of an ensemble,

$$A=\int w(q)\{a_qa_q'|\tau\}dq; \tag{21}$$

it will then satisfy Eqs. (15) to (18) inclusive, with

$$B(\mathbf{x},\mathbf{x}',\omega)=2\pi\int w(q)\alpha_q(\mathbf{x},\omega)\alpha_q(\mathbf{x}',\omega)dq, \tag{22}$$

provided the integrals of Eqs. (21) and (22) converge well enough. A necessary condition that $A$ be the convolution of a real function $a$ can now be formulated: when the function $B$ defined by Eq. (22) is substituted into Eq. (19), the latter must have exactly one, nondegenerate and positive, eigenvalue. This will certainly not always be the case.

Thus, it has been shown that those solutions of Eqs. (8) that are obtained by the method of ensembles are not always convolutions. That they are not always correlations of Class *AL* functions follows, because if they were, the function $A$ of Eq. (21) could not be expanded as a Fourier integral, and this is usually the case.

## V. MODIFIED FORMS OF THE STATISTICAL SOLUTION

The restriction to real ensembles is often inconvenient. It can be removed in various ways, one of which is the following. Let $p(\mathbf{x},t)$, $a(\mathbf{x},t)$ be a complex solution of Eq. (1.1) and construct the ensemble

$$p_q=pe^{iq}+p^*e^{-iq},\quad a_q=ae^{iq}+a^*e^{-iq},$$

with $w=1/4\pi$. Then Eq. (12) yields

$$P=\Re\{p^*p'|\tau\},\ \cdots,\ A=\Re\{a^*a'|\tau\}.$$

This can be used to generalize Eq. (12) into

$$P=\Re\int w(q)\{p_q^*p_q'|\tau\}dq,\ \text{etc.}\qquad (2$$

and thus enables one to make use of complex ensembl

Another modification of Eq. (12) is obtained follows: with the ensemble $p(q)$, $a(q)$, construct ensemble $p(q_1)+p(q_2)$, $a(q_1)+a(q_2)$ with double t number of parameters, and the symmetric weig function $w_2(q_1,q_2)=w_2(q_2,q_1)$. Using the abbreviatio

$$w_1(q)=\int w_2(q,q_2)dq_2,$$

Eq. (12) yields

$$P=2P_1+2P_2,\ \text{etc.},$$

where

$$P_1=\int w_1(q)\{p(q)p'(q)|\tau\}dq,\qquad (24$$

$$P_2=\int\int w_2(q_1,q_2)\{p(q_1)p'(q_2)|\tau\}dq_1dq_2.\qquad (24$$

One can also construct the ensemble $p(q_1)+\cdot$ $+p(q_N)$, $a(q_1)+\cdots+a(q_N)$, with $N$ times the numb of parameters, and a symmetric weight functi $w(q_1\cdots q_N)$. Then, if $w_1$ and $w_2$ are appropriate defined, Eq. (12) yields

$$P=NP_1+N(N-1)P_2.$$

Thus it follows that $P_2$ is itself a solution of the E (8), (8.1), (8.2), even though superposition with neg tive coefficients is not generally permissible. Wh solutions of the form of Eq. (24.2) are useful, t method of derivation shows that they need not be giv a special place in the general theory.

## VI. STATISTICALLY UNIFORM FREE FIELDS

As a first example of these methods, the homogeneo Eq. (1) will be considered, under the assumption th Eq. (2) has solutions of the form

$$f=\exp[ik(\omega)\mathbf{q}\cdot\mathbf{x}],\qquad (2$$

as is frequently the case, $\omega$ taking on all real values, a $k$ being a function of $\omega$, while $\mathbf{q}$ is a unit vector th can be varied independently of $\omega$. If the functi $g(\mathbf{q},\omega)$ is appropriately chosen,

$$p(\mathbf{q})=\int g(\mathbf{q},\omega)\exp[i(k\mathbf{q}\cdot\mathbf{x}-\omega t)]d\omega\qquad (25$$

will be an ensemble of Class $I$ solutions. The element solid angle $d\mathbf{q}$ associated with the unit vector $\mathbf{q}$ can sed as $wdq$. Then Eq. (23) yields

$$pp'|\tau\rangle=2\pi\int\int|g(\mathbf{q},\omega)|^2\cos[k\mathbf{q}\cdot\boldsymbol{\xi}-\omega\tau]d\omega d\mathbf{q},\quad(26)$$

here

$$\boldsymbol{\xi}=\mathbf{x}-\mathbf{x}'.\quad(26.1)$$

Since this correlation depends only on the difference $-\mathbf{x}'$, it represents a solution that is statistically iform throughout space. The mean-square value of $p$ any point in space is

$$\langle p^2\rangle=\langle pp|0\rangle=2\pi\int\int|g|^2d\omega d\mathbf{q}$$

d is also independent of position. In most cases the rrelation of $\partial p/\partial t$ with the gradient is associated with e flux of energy; by differentiating Eq. (26) one tains

$$\nabla p)(\partial p'/\partial t)|\tau\rangle=2\pi\int\int\omega k\mathbf{q}|g|^2\cos[k\mathbf{q}\cdot\boldsymbol{\xi}-\omega\tau]d\omega d\mathbf{q},$$

hence

$$\langle(\nabla p)(\partial p/\partial t)\rangle=2\pi\int\int\omega k\mathbf{q}|g|^2d\omega d\mathbf{q}.$$

lthough uniform, the field is thus not statistically tropic unless $|g|$ is independent of $\mathbf{q}$. More detailed amples of such calculations are to be found in ference 6.

The function $|g|^2$ may be called the spatio-temporal ectrum of $p$; in Planck's terminology, it is the ectral component of the specific energy density.[8] In e above discussion, it appears as an arbitrary func-n, and would be rendered unique only by a more mplete formulation of the problem.

## VII. DISSIPATIVE SYSTEMS

As an example of the treatment of the inhomogeneous q. (1.1), it is simplest to take the case of a frictionally ssipative system, for which the Eq. (2) has no real genvalues. Then, to the function

$$a=\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)],\quad(27.1)$$

e Eq. (1.1) associates

$$p=Z(\mathbf{k}\omega)\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]\quad(27.2)$$

e function $Z$ having no poles or other infinities for l values of $\mathbf{k}$ and $\omega$. The ensemble

$$a(\mathbf{k})=\int g(\omega)\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\omega,$$
$$(27.3)$$
$$p(\mathbf{k})=\int Zg(\omega)\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\omega,$$

is constructed, $\mathbf{k}$ now taking the place of $q$. Statistically uniform solutions can be constructed as before, but it is instructive to use Eq. (24.2) with $w(\mathbf{k}_1,\mathbf{k}_2)$ replacing $w_2(q_1,q_2)$. Then

$$\langle aa'|\tau\rangle=2\pi\Re\int\int\int w(\mathbf{k}_1\mathbf{k}_2)|g(\omega)|^2$$
$$\cdot\exp[i(\mathbf{k}_1\cdot\mathbf{x}-\mathbf{k}_2\cdot\mathbf{x}'-\omega\tau)]d\mathbf{k}_1d\mathbf{k}_2d\omega,\quad(28.1)$$

$$\langle pp'|\tau\rangle=2\pi\Re\int\int\int w(\mathbf{k}_1\mathbf{k}_2)|g(\omega)|^2Z(\mathbf{k}_1,\omega)Z^*(\mathbf{k}_2,\omega)$$
$$\cdot\exp[i(\mathbf{k}_1\cdot\mathbf{x}-\mathbf{k}_2\cdot\mathbf{x}'-\omega\tau)]d\mathbf{k}_1d\mathbf{k}_2d\omega,\ \text{etc.}\quad(28.2)$$

Since these solutions depend on both $\mathbf{x}$ and $\mathbf{x}'$, and not merely on $\mathbf{x}-\mathbf{x}'$, they represent statistically nonuniform solutions. Thus the mean square of $p$ is

$$\langle p^2\rangle=\langle pp'|0\rangle$$
$$=2\pi\Re\int\int\int w(\mathbf{k}_1,\mathbf{k}_2)|g|^2Z(\mathbf{k}_1,\omega)Z^*(\mathbf{k}_2,\omega)$$
$$\cdot\exp[i(\mathbf{k}_1-\mathbf{k}_2)\cdot\mathbf{x}]d\mathbf{k}_1d\mathbf{k}_2d\omega,\quad(28.3)$$

and varies from point to point. Again, more detailed examples of such fields have been given in reference 6, though without using the systematic methods here developed.

## VIII. THE SCATTERING OF RADIATION BY FLUCTUATIONS OF THE INDEX OF REFRACTION

If a plane monochromatic wave passes through a region in which the index of refraction varies irregularly with space and time, the radiation will be scattered and converted into nonmonochromatic radiation. This process will be treated in detail as a last example of the above methods. If the scattered radiation is $p$, and the index of refraction is $1+a$, while the incident wave is $p_0=\cos(\boldsymbol{\kappa}\cdot\mathbf{x}-\nu t)$, with $\nu=\kappa c$, the Eq. (1.1) takes the form[9]

$$c^{-2}\partial^2p/\partial t^2-\nabla^2p=2\kappa^2a\cos(\boldsymbol{\kappa}\cdot\mathbf{x}-\nu t).\quad(29)$$

It will be supposed that the inhomogeneity $a$ can be represented by an ensemble of functions

$$a_{\mathbf{q}}=a_0(\mathbf{x}-\mathbf{q},t),\quad(30)$$

$a_0(\mathbf{x},t)$ having its maximum or center at the origin, and $\mathbf{q}$ therefore being the point in space at which $a_{\mathbf{q}}$ is centered. The vector $\mathbf{q}$ will be taken as the ensemble variable; the significance of the weight function $w(\mathbf{q})$ will appear below.

If

$$a_0(\mathbf{x},t)=\int\int A(\mathbf{k},\omega)\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\mathbf{k}d\omega,\quad(31)$$

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M. Planck, *Vorlesungen über die Theorie der Wärmestrahlung* A. Barth, Leipzig, 1912), Chap. I.

[9] Squares of $a$ have been neglected.

Eq. (12) yields

$$\langle aa'|\tau\rangle=(2\pi)^4\int\int\int A(\mathbf{k},\omega)A^*(\mathbf{k}',\omega)W(\mathbf{k}-\mathbf{k}')\cdot\exp[i(\mathbf{k}\cdot\mathbf{x}-\mathbf{k}'\cdot\mathbf{x}'-\omega\tau)]d\mathbf{k}d\mathbf{k}'d\omega, \quad (32)$$

where

$$W(\boldsymbol{\alpha})=\int w(\mathbf{q})\exp(-i\boldsymbol{\alpha}\cdot\mathbf{q})d\mathbf{q}/(2\pi)^3. \quad (33)$$

If, moreover, $W(\boldsymbol{\alpha})$ has a narrow peak at $\boldsymbol{\alpha}=0$, it will be justifiable to replace $\mathbf{k}$ and $\mathbf{k}'$, in the $A$ factors, both by

$$\mathbf{m}=\tfrac{1}{2}(\mathbf{k}+\mathbf{k}').$$

Using the notation,

$$\boldsymbol{\alpha}=\mathbf{k}-\mathbf{k}', \quad \boldsymbol{\xi}=\mathbf{x}-\mathbf{x}', \quad \mathbf{r}=\tfrac{1}{2}(\mathbf{x}+\mathbf{x}'),$$

Eq. (32) then becomes

$$\langle aa'|\tau\rangle=(2\pi)^4 w(\mathbf{r})\int\int|A(\mathbf{m},\omega)|^2 \times\exp[i(\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau)]d\mathbf{m}d\omega, \quad (34)$$

$$=w(\mathbf{r})\phi(\boldsymbol{\xi},\tau). \quad (34.1)$$

If the function $a_0$ is normalized so that $\phi(0,0)=1$, then $w(\mathbf{r})$ represents the mean-square fluctuation of the refractive index at the point $\mathbf{r}$. If the distance in which this changes appreciably is much greater than the dimensions of the region in which $a_0$ varies, the above approximation is justified. The function

$$\Phi(\mathbf{m},\omega)=(2\pi)^4|A(\mathbf{m},\omega)|^2 \quad (35)$$

in the spatio-temporal spectrum of the fluctuation, and is independent of position.[10]

To proceed further, it is necessary to determine $p_{\mathbf{q}}$, the outgoing-wave solution of Eq. (29) when $a$ is replaced by $a_{\mathbf{q}}$. The right side of that equation may be written

$$2\kappa^2 a_{\mathbf{q}}\cos(\boldsymbol{\kappa}\cdot\mathbf{x}-\nu t)=\mathcal{R}\int\int B(\mathbf{q},\mathbf{k},\omega)\times\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\mathbf{k}d\omega/c^2, \quad (36)$$

where the integration over $\omega$ (here and hereafter) is from $0\rightarrow\infty$ only, and

$$B(\mathbf{q},\mathbf{k},\omega)=2\nu^2\{A(\mathbf{k}-\boldsymbol{\kappa},\omega-\nu)\exp[-i(\mathbf{k}-\boldsymbol{\kappa})\cdot\mathbf{q}] +A(\mathbf{k}+\boldsymbol{\kappa},\omega+\nu)\exp[-i(\mathbf{k}+\boldsymbol{\kappa})\cdot\mathbf{q}]\}. \quad (37)$$

The required solution is then

$$p_{\mathbf{q}}=\mathcal{R}\int\int\int i[B(\mathbf{q},\mathbf{k},\omega)/(kc+\omega)] \cdot\exp\{i[\mathbf{k}\cdot\mathbf{x}-\omega t-u(kc-\omega)]\}d\mathbf{k}d\omega du, \quad (38)$$

the integration over the auxiliary variable $u$ also be always from $0\rightarrow\infty$. That this is a solution of Eq. ( is most readily seen by direct substitution on the side; the integration with respect to $u$ can then performed, and the result is seen to be the right sid Eq. (36). That this is the outgoing solution beco obvious on making the change of variable $s=t-u$, si then, the integration over $s$ is from $-\infty\rightarrow t$, and is s to vanish identically for $t=-\infty$, but not so for $t=+$

The convolution of $p_{\mathbf{q}}$ is then given by the nine integral

$$\{p_{\mathbf{q}},p_{\mathbf{q}}'|\tau\}=2\pi\mathcal{R}\int\int\int\int\int[B(\mathbf{q},\mathbf{k},\omega)B^*(\mathbf{q},\mathbf{k}',\omega)/ (kc+\omega)(k'c+\omega)]e^{i\Theta}d\mathbf{k}d\mathbf{k}'d\omega du du'$$

where

$$\Theta=\mathbf{k}\cdot\mathbf{x}-\mathbf{k}'\cdot\mathbf{x}-\omega\tau-u(kc+\omega)+u'(k'c+\omega).$$

This must be multiplied by $w(\mathbf{q})$ and integrated the variables $\mathbf{q}$ in order to obtain the correlation. Si only the factors $B$ depend on $\mathbf{q}$, one may first evalu

$$C=2\pi\int B(\mathbf{q},\mathbf{k},\omega)B(\mathbf{q},\mathbf{k}',\omega)w(\mathbf{q})d\mathbf{q}.$$

Using Eq. (33), this is

$$\begin{aligned}C=4\nu^4(2\pi)^4\{&A(\mathbf{k}-\boldsymbol{\kappa},\omega-\nu)A^*(\mathbf{k}'-\boldsymbol{\kappa},\omega-\nu)W(\mathbf{k}-\mathbf{k}'\\ &+A(\mathbf{k}+\boldsymbol{\kappa},\omega+\nu)A^*(\mathbf{k}'+\boldsymbol{\kappa},\omega+\nu)W(\mathbf{k}-\mathbf{k}')\\ &+A(\mathbf{k}-\boldsymbol{\kappa},\omega-\nu)A^*(\mathbf{k}'+\boldsymbol{\kappa},\omega+\nu)W(\mathbf{k}-\mathbf{k}'-2\\ &+A(\mathbf{k}+\boldsymbol{\kappa},\omega+\nu)A^*(\mathbf{k}'-\boldsymbol{\kappa},\omega-\nu)W(\mathbf{k}-\mathbf{k}'+2\end{aligned}$$

Because $W(\boldsymbol{\alpha})$ has a sharp maximum at $\boldsymbol{\alpha}=0$, this is a sufficient approximation,

$$\begin{aligned}C=4\nu^4(2\pi)^4&\\ \times\{[&|A(\mathbf{m}-\boldsymbol{\kappa},\omega-\nu)|^2+|A(\mathbf{m}+\boldsymbol{\kappa},\omega+\nu)|^2]W\\ &+A(\mathbf{m},\omega-\nu)A^*(\mathbf{m},\omega+\nu)W(\boldsymbol{\alpha}-2\boldsymbol{\kappa})\\ &+A(\mathbf{m},\omega+\nu)A^*(\mathbf{m},\omega-\nu)W(\boldsymbol{\alpha}+2\boldsymbol{\kappa})\}.\end{aligned}$$

The integration over $\omega$ will be only from $\omega=0\rightarrow\infty$ $A(\mathbf{k},\omega)$ has a maximum at $\omega=0$ of width less tha only the first term of this expression will contri appreciably to the integral, so that the approximat

$$C=4\nu^4\Phi(\mathbf{m}-\boldsymbol{\kappa},\omega-\nu)W(\boldsymbol{\alpha})$$

may be used. Then one obtains

$$\langle pp'|\tau\rangle=4\nu^4\mathcal{R}\int\int\int\int\int[\Phi(\mathbf{m}-\boldsymbol{\kappa},\omega-\nu)/ (mc+\omega)^2]W(\boldsymbol{\alpha})e^{i\Theta}d\mathbf{k}d\mathbf{k}'d\omega du du'.$$

Making the change of variables

$$v=u-u', \quad \sigma=\tfrac{1}{2}c(u+u')$$

and, in $\Theta$, the approximations

$$k=m+\tfrac{1}{2}\boldsymbol{\alpha}\cdot\mathbf{m}_1, \quad k'=m-\tfrac{1}{2}\boldsymbol{\alpha}\cdot\mathbf{m}_1, \quad \mathbf{m}_1=\mathbf{m}/m$$

---

[10] This results from the assumption that the members of the ensemble differ only as to their center. The introduction of additional ensemble variables would generalize the Eq. (35).

. (39) becomes

$$'|\tau\rangle=(4\nu^4/c)\mathfrak{R}\int\int\int\int\int [\Phi(\mathbf{m}-\boldsymbol{\kappa},\omega-\nu)/(mc+\omega)^2]W(\boldsymbol{\alpha}) \cdot\exp\{i[\boldsymbol{\alpha}\cdot\mathbf{r}+\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau+v(mc-\omega) +\sigma\boldsymbol{\alpha}\cdot\mathbf{m}_1]\}d\mathbf{m}d\boldsymbol{\alpha}d\omega dv d\sigma, \quad (40)$$

integration over $v$ being from $-2\sigma/c\rightarrow+2\sigma/c$ and
t over $\sigma$ from $0\rightarrow\infty$. The integrations over $\boldsymbol{\alpha}$ and $v$
then be performed at once, leading to

$$'|\tau\rangle=(8\nu^4/c)\int\int\int[\Phi(\mathbf{m}-\mathbf{k},\omega-\nu)/ (mc+\omega)^2]w(\mathbf{r}-\sigma\mathbf{m}_1) \cdot\{\sin[2\sigma(m-\omega/c)]/(mc-\omega)\} \cos[\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau]d\mathbf{m}d\omega d\sigma. \quad (41)$$

f the point $\mathbf{r}$ is well outside the scattering region, the
tor $w(\mathbf{r}-\sigma\mathbf{m}_1)$ will be different from zero only when
s very large; this entails that the factor immediately
lowing $w$ will have a sharp maximum at $m=\omega/c$. The
egration over $m$ can therefore be performed with a
h degree of precision by replacing $m$ by $\omega/c$ every-
ere except in this factor; then

$$'|\tau\rangle=(2\pi\kappa^4)\int\int\Phi[(\omega/c)\mathbf{m}_1-\boldsymbol{\kappa},\omega-\nu]S(\mathbf{r},\mathbf{m}_1) \cdot\cos[(\omega/c)(\mathbf{m}_1\cdot\boldsymbol{\xi}-c\tau)]d\mathbf{m}_1 d\omega, \quad (42)$$

ere $d\mathbf{m}_1$, is the element of solid angle associated to
, and the "optical depth" is

$$S(\mathbf{r},\mathbf{m}_1)=\int_{\sigma=0}^{\infty}w(\mathbf{r}-\sigma\mathbf{m}_1)d\sigma. \quad (43)$$

he scattered radiation therefore consists (to this
proximation, at least) entirely of free waves traveling
h the velocity $c$—in marked contrast to the fluctua-
ons of the index of refraction, that involve waves
all velocities. The intensity of the scattered radiation
btained by setting $\xi=0$, $\tau=0$ in Eq. (42) and is a
ction of $\mathbf{r}$; the radiation field is therefore not homo-
eous. The spatio-temporal spectrum also depends
$\mathbf{r}$, in contrast to that of the fluctuations causing the
ttering. The scattered radiation is not monochro-
tic, even when the direction of propagation is dis-
arded, but does have a peak at $\omega=\nu$. Apart from
se generalities, the Eq. (42) contains information
cerning the line shape and other coherence properties of the scattered radiation, which it would not be profitable to discuss here.

## IX. SOME UNSOLVED PROBLEMS

It appears that the ensemble method, as described above, is capable of yielding useful results in many problems. However, as has been noted, it evades the analytic representation of the solution being averaged. There are many reasons why it would be desirable to have such representations. Without them, it is difficult to understand the precise relation between the ensemble and the physical reality whose average is being calculated. It is almost certain that there will be many Class *AC* solutions that yield the same correlations: do these differ only in the arrangement of one and the same set of events, or, are there more fundamental differences? Is it justified to consider the ensemble as an artificially ordered set of Class *I* solutions, whose random superposition in space-time constitutes the Class *AC* solution? How does the weight function enter into the analytic representation of the Class *AC* solutions? One may attempt to answer these questions on the basis of common sense, but reflection always raises doubt.

Another set of problems arises when one considers higher-order correlations, such as $\langle f(\mathbf{x},t)g(\mathbf{x}',t-\tau)\times h(\mathbf{x}'',t-\sigma)\rangle$. Such correlations occur in the formulation of many physical problems.[4] and the complete set of all orders presumably determines the Class *AC* solution uniquely, in some sense of the word. If one attempts to generalize the method of ensembles so that these higher correlations may be calculated, many difficulties arise. These are connected with the generalization of the Schwarzian inequalities. There are not only a great number of such inequalities, but there are some that are satisfied only by correlations, and not by convolutions. For this reason, it has not been possible to extend the method of ensembles in this direction.

The reason for these difficulties is not too clear. In one sense, they exist in even the simplest case, for $\langle 1\rangle=1$ while $\{1\}=\infty$, and this prevents one from calculating $\langle p\rangle$ by the method of ensembles. Yet, as has been shown, this does not prevent the calculation of $\langle pp'|\tau\rangle$ by that method, providing that $\langle p\rangle=0$. Therefore, it is possible that some, at least, of the higher-order correlations can be calculated by this same method, providing sufficient ingenuity is exercised. It is also possible that the difficulty is more fundamental, and that the higher correlations can be calculated only after an analytic representation of the field has been found.

JOURNAL OF PALEONTOLOGY, VOL. 27, NO. 4, pp. 569–576, 5 TEXT FIGS., JULY 1953

# BURIED OYSTER REEFS IN SOME TEXAS BAYS[1]

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Santa Barbara College, University of California, Santa Barbara

ABSTRACT—Probing with poles and pipes revealed the presence of many buried oyster reefs in Aransas, Mesquite and San Antonio bays, Texas. Evidence suggests that modern reefs retain their narrow surface width at depth. Probing data are too scanty in most areas to warrant plotting the limits of individual buried reefs. Shell dredging operations have shown that such reefs are occasionally as much as 12 feet thick. The old reefs are judged to have disappeared owing to unfavorable changes in salinity.

## INTRODUCTION

THIS paper is concerned with oyster reefs buried at various depths below the present bottoms in three large shallow bays on the south central Texas coast (fig. 1). All three bays are more or less cut off from the open Gulf of Mexico by low-lying barrier islands. The northernmost and largest of these bays is San Antonio, which includes two smaller connecting water bodies, Guadalupe and Hynes bays. San Antonio Bay is roughly 12 miles long in a north direction and 6 miles wide. The depth is nowhere greater than 7 feet. Mesquite Bay, farther south, is connected with San Antonio Bay by several narrow passes between low islets and exposed oyster reefs. Mesquite Bay is about 4 miles long and 3 miles wide and has a maximum depth of 4½ feet. Mesquite Bay, unlike San Antonio Bay, has a direct connection with the gulf at present through Cedar Bayou, a narrow, shallow pass. Aransas Bay, the southernmost body of water under discussion, is connected with Mesquite Bay in much the same way that Mesquite and San Antonio bays are connected. Aransas Bay is the only one of the group having a deep water connection with the open gulf. This connection is Aransas Pass, one of three major breaches in the barrier island system of south Texas. Aransas Bay is roughly 14 miles long in a northeast direction and 4 miles wide with a greatest depth of 13 feet.

Buried reefs have been detected at depths ranging from a few inches to as much as 14 feet below the bottom of the modern bays. Because data on the buried reefs were mostly obtained incidental to other work, little information is available on reef dimensions. It seems reasonable, however, to assume that buried reefs, like their modern counterparts, are mostly long and narrow in plan and do not cover broad areas. The distribution of the buried reefs apparently has no relation to the distribution of modern reefs.

The term "reef" as used in this paper refers to a narrow linear accumulation of shells, mostly those of the oyster (*Crassostrea virginica*), resulting from the successive growth of generations of oysters in the same place. Living oysters frequently, but not invariably, occupy the exposed surfaces of such reefs.

## ACKNOWLEDGMENTS

The author is indebted to the various personnel of A.P.I. Project 51 who have worked with him in the field during 1951 and 1952. F. P. Shepard and other members of the Scripps Institution of Oceanography have offered many helpful suggestions and criticisms of the manuscript.

## FIELD WORK

The field investigation was carried out in two parts: the first during the summer of 1951 and the second in the winter of 1952. Probing operations were carried out from the deck of a small shrimp boat with sufficiently shallow draft to allow it to reach most parts of the bays without difficulty. Two probes were used: the first, a 21 foot length of half-inch I.D. galvanized pipe pointed at one end and marked off in one foot intervals; the second probe an ordinary 12 foot bamboo pole, similarly marked. The probes were pushed manually into the bay bottom from the boat. The penetration into the bottom was calculated by noting the depth of water and subtracting that amount from the reading on the probe at the water surface. Although distinctions between different materials encountered in probing are somewhat subjective, it is possible, in most cases, to distinguish mud, shell and sand. The bamboo probe is better adapted for detecting thin sand and shell layers than the pipe probe, but will not penetrate more than a few inches of hard sand or shell. Inasmuch as thin sand or shell layers often were found above true buried reefs, the pipe probe was used most of the time. Longer probes would have been desirable, but would probably have been too difficult to handle manually. The pipe probe was often hard to pull up from maximum penetration. Future operations of this type might be more effectively carried out with a longer probe constructed of aluminum pipe with a steel point; this would materially reduce the weight of the unit.

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[1] This investigation was supported by a grant from the American Petroleum Institute, Project 51.

Selection of stations for probing was more or less haphazard during the early part of the first field season. When it was found that probing could detect many buried reefs, it was instituted as regular procedure at most stations subsequently occupied by the boat. Stations during the first field season were selected mainly to cover the

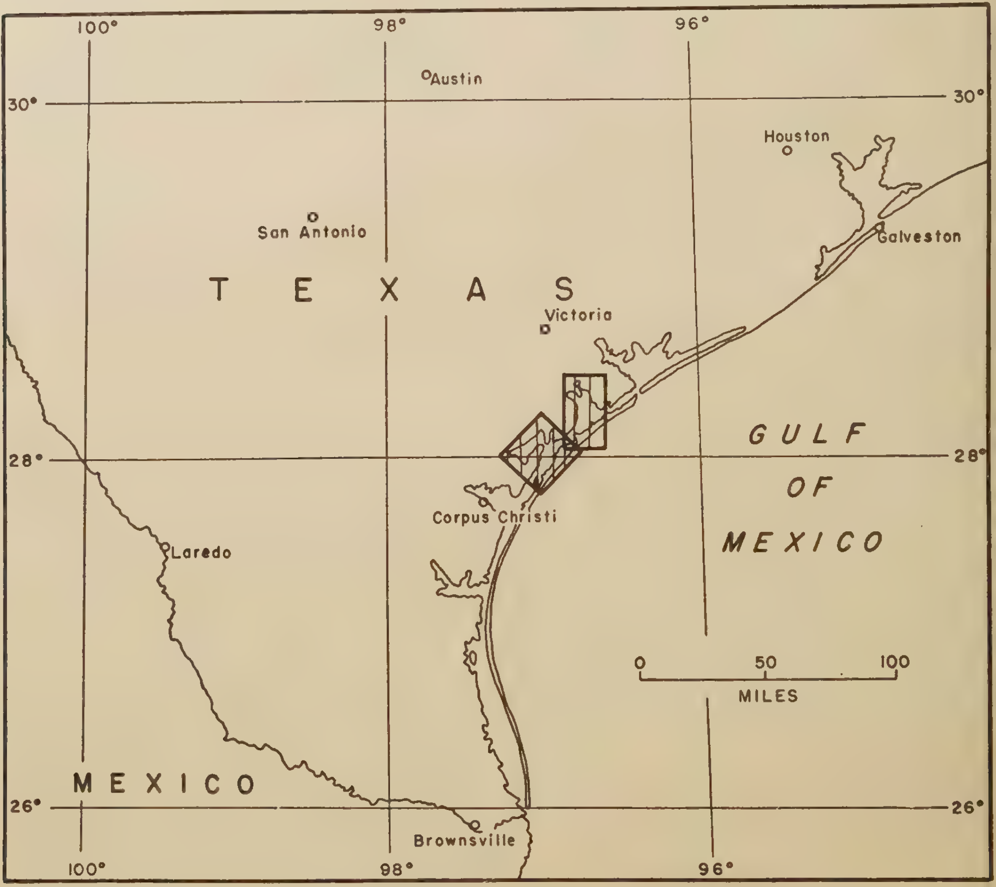

FIG. *1*—Outline map of part of Texas showing location of areas investigated.

area as closely as possible and were not generally concentrated in any area. During the second field season, stations were selected to fill in gaps left by the first season's coverage, and to investigate certain areas in greater detail which were believed to be of special importance. Only three traverses were made solely for probing purposes and all three of these were located in San Antonio Bay. Two traverses were made in a north-south direction in the central part of the bay in order to discover the limits of a large reef buried about three feet below the bottom. Original data indicating the presence of this reef had been assembled from three or four east-west traverses made during the first field season. The third traverse was run across (normal to the long direction) a modern reef in order to provide some information on the lateral and vertical extent of a living shell reef. Geographic distribution of the stations and depths to which probing extended are shown in figure 2.

### EXTENT OF MODERN OYSTER REEFS NEAR TEXAS COAST

Modern oyster reefs in Texas bays are usually long, relatively narrow accumulations of shell in a prevailingly soft mud bottom. The narrow, linear character of the reefs is more evident in the central parts of the bays than near the margins. Shell reefs are often less distinct near shore where loose shell and sand have been scattered over the bottom by wave action. The tendency of reefs to grow out into the bays at right angles to the shore is evident from an examination of figure 3, and has been discussed extensively by Grave (1905, p. 261) who observed such reefs in North Carolina. Most modern reefs in these Texas bays occur at depths less than 6 feet and many are partially exposed as long islands during periods of low water (fig. 4).

Shell reefs are common in central and upper San Antonio Bay, but are absent in tributary Hynes and Guadalupe bays. Lower San Antonio Bay has few reefs except where it joins Mesquite and Espiritu Santo bays and where a single long narrow reef (Panther Reef) divides this part of the bay nearly in half. This particular reef is about 5 miles long and seldom more than 150 yards wide. Closely spaced reefs and shell bottom characterize much of the area between Mesquite and Aransas bays. In Mesquite Bay proper, however, shell reefs are not abundant. Aransas Bay, on the other hand, has abundant shell reefs in its upper third, near where it joins Mesquite, St. Charles and Copano bays, but a scarcity in the lower bay.

Little information is available on the total thickness of the modern reefs in this region. The probing equipment used in this study was not satisfactory for penetrating more than a foot of ordinary shell reef. Operators of shell dredges have reported vertical thicknesses of as much as 20 feet. Some of these commercial operators, however, maintain that 20 feet is an exaggeration and that 12 feet is about the greatest thickness encountered (J. Heldenfels, personal communication). Nevertheless, Galtsoff (1941, p. 2) mentions a 20 foot thickness of some shell reefs in this area and Richards (1939, p. 1890) discusses the occurrence of shell reefs in Copano Bay at 100 feet below sea level as revealed by water well cores.

Probe traverses normal to Long Reef in Aransas Bay and Dagger Reef in San Antonio Bay suggest that reefs do not become appreciably wider with depth below the bottom. For example, probing 8 feet into the sediment 150 feet southwest of Long Reef disclosed no shell layers at all. Another probe station, about the same distance northeast of Long Reef, encountered no shell beds 9 feet below the mud surface. In San Antonio Bay, the situation is similar; Dagger Reef showed a similar lack of width at depth. One hundred and fifty feet northwest of the exposed reef a 6 foot penetration failed to find any reef material. A cross-section of Long Reef is shown in figure 5. Additional evidence for the lack of increasing width with depth is provided by a number of separate probe stations made close to exposed reefs. At least eight such probes, located within 300 feet of a reef, penetrated 8 to 14 feet of mud without striking any buried shell reefs.

### BURIED REEFS

Buried reefs have been found in Aransas, Mesquite and San Antonio bays. A few probes made in Copano and Espiritu Santo bays indicated buried shell reefs there as

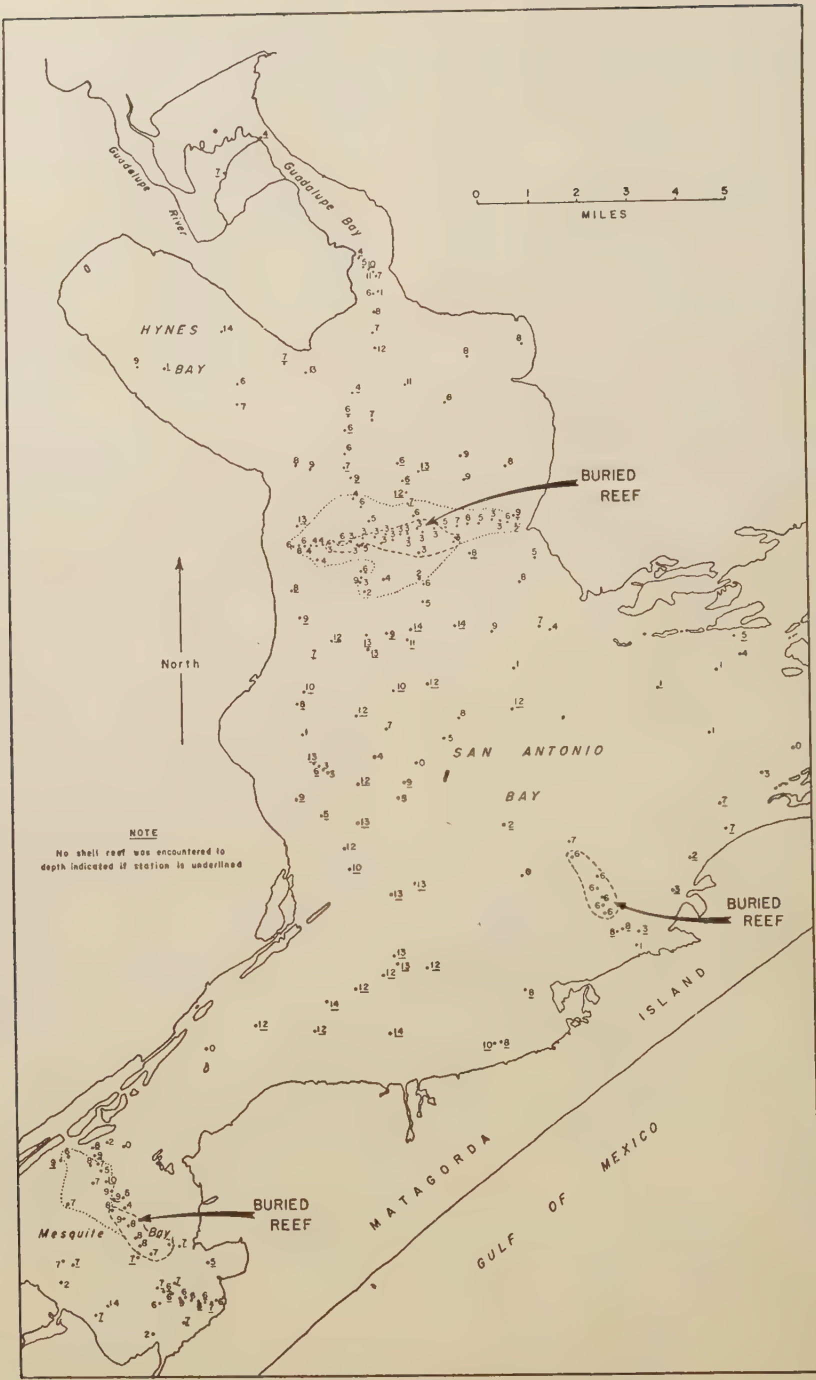
Guadalupe River
Guadalupe Bay
0 1 2 3 4 5
MILES
HYNES BAY
BURIED REEF
North
SAN ANTONIO BAY
NOTE
No shell reef was encountered to depth indicated if station is underlined
BURIED REEF
Mesquite Bay
BURIED REEF
MATAGORDA ISLAND
GULF OF MEXICO

FIG. 2—Map showing the distribution of probe stations and depth of penetration in San Antonio an
Mesquite bays. Dashed lines indicate probable limits of larger buried reefs.

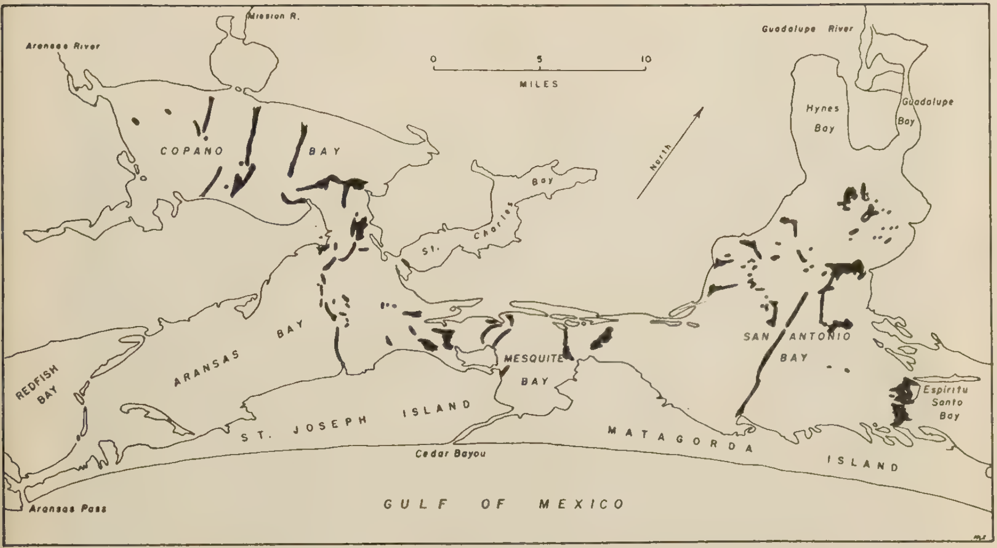

FIG. *3*—Map showing distribution of modern shell reefs.

well. Collier and Hedgpeth (1950, p. 139) report buried shell reefs from other Texas bays and it is not suggested that the occurrences described in this paper are unique. In the majority of probes, a buried reef was detected, despite the fact that many of the probes penetrated the bottom less than 5 feet. One part of the area, however, showed a surprising absence of buried reefs: southwestern San Antonio Bay. In this particular place thirteen probes were made with penetrations ranging from 8 to 14 feet and none encountered anything but soft mud. There are no modern reefs in this area. Other areas lacking modern reefs such as Hynes, Guadalupe and central Mesquite bays show evidence of buried reefs. Reefs in the first two bays may have been killed by prolonged exposure to fresh water associated with severe floods. Mesquite Bay reefs, on the other hand, may have been subjected to prolonged exposure to water of high salinity from the open gulf, or to burial by sand from the barrier islands washed into the bay during storms. Collier and Hedgpeth (1950, p. 138) point out that lowered salinities following continued heavy rains occasionally kill oysters in the inner bays. The same authors, and Galtsoff (1931, p. 9) show that high salinities have an equally disastrous effect on the oyster population. Moore (1907, pp. 61–62) cites instances where Texas reefs were nearly killed by sand washed over them by hurricanes. Once a reef community is killed, it faces eventual burial by sediment. The frequency and wide distribution of buried reefs suggests that shell reefs have been a prominent feature of the bays for some time, although their distribution shows a changing pattern.

Probing stations were not generally located close enough together to delimit buried reefs accurately. It is obvious that many linear shell reefs could easily be overlooked, even if probe stations covered the entire area on a half-mile grid. Despite this difficulty, probing seems to indicate the presence of a continuous buried reef in at least three different places in the area (fig. 2). One of these is a flat area in central San Antonio Bay underlain at a depth of from $2\frac{1}{2}$ to $3\frac{1}{2}$ feet by what appears to be a continuous reef. Possible greater extent is indicated by other probes which encountered hard shell at greater depths in this vicinity. A smaller, apparently more linear reef, occurs 6 feet below the bottom in southeastern San Antonio Bay. In Mesquite Bay, the probe was stopped many times after about 7 to 9 feet of penetration. Some of these probes, however, terminated in hard sand rather than in shell. Nevertheless, a small area in

FIG. *4*—Portion of Dagger Reef, San Antonio Bay, looking southwest, during a period of low water February 29, 1952.

the central part of the bay probably is underlain by reef material at a depth of 8 to 9 feet.

### CAUSE OF REEF BURIAL

Price (1947, p. 1658) expresses the opinion that burial of reefs must be attributed to sedimentation accompanying the post-glacial rise in sea-level and that it did not occur during the present stand of the gulf. F. P. Shepard (personal communication), however, by means of a study of United States Coast and Geodetic Survey charts published during the past hundred years, has found evidence that as much as one foot of sediment has been deposited in certain places in these bays during the last 60 or 70 years.

Oysters must be exposed to circulating water and do not live buried in sediment[2] or to any great extent covered by other oysters. Inasmuch as this and other investigations have shown that old shell reefs occur 14 feet or more below present bay bottoms, and the region shows no evidence of general subsidence, it follows that the bays mus have been *at least 14 feet deeper* at some tim in the past. This depth, based on information obtained from probing devices used i this study should be regarded as a minimum Price (1933, pp. 924-927) points out tha San Antonio Bay is a drowned river valle modified by wave action and sedimentation and that the river excavated this forme valley 50 to 75 feet or more below presen sea-level. Deepening of the river channe may have been related to a general lowerin of sea-level rather than to any diastrophi elevation of the land because of the commo occurrence of similar estuaries along mos of the Texas coast and many other coasts The latest well-established lower sea-leve occurred near the close of the Pleistocene perhaps 23,000 years ago (Zeuner, 1945 p. 251). A possible sequence of events leading up to present conditions is therefore se forth: *first*, marine Pleistocene sediment were deposited that now crop out, amon other places, along the western side of Sa Antonio Bay; *second*, a late Pleistocen lowering of sea-level took place accompanie by down-cutting of the river valleys acros the marine Pleistocene deposits; *third*, th post-Pleistocene rise in sea-level flooded th

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[2] Except in the case of long thin oysters called mud oysters found in Copano Bay and Redfish Bay, Aransas County, Texas, which may have their bases a foot below ths surface.

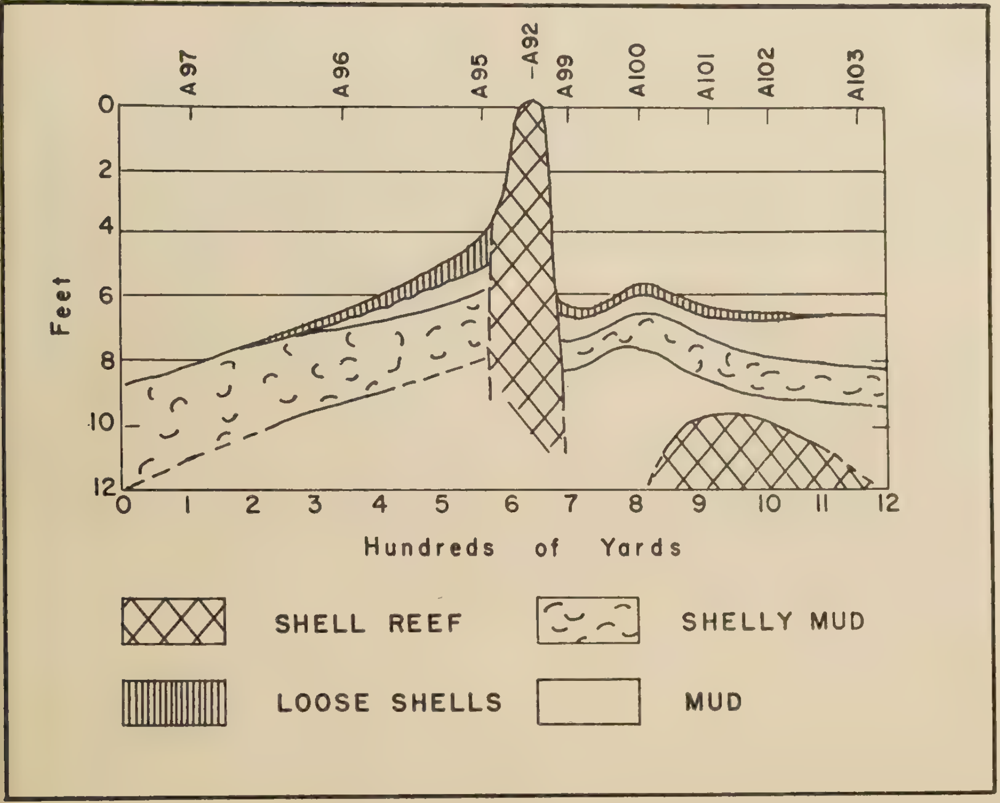

FIG. 5—Cross-section of Long Reef, Aransas Bay. Position of probe stations indicated by numbers. Vertical scale greatly exaggerated.

lower river valleys forming estuaries. These estuaries may have been subsequently widened by wave action (Price, 1933, p. 924) and may have begun to act as traps for sediment carried in by the rivers. It is probable that oyster reefs started to grow in San Antonio and Copano bays first, because the entering rivers would be expected to reduce salinities to values suitable for oyster growth. Aransas and Mesquite bays, being then open to the gulf, probably had few, if any, oyster reefs until the barrier islands formed and closed the bays off from the gulf. Probing information suggests that fewer deeply buried reefs occur in Mesquite Bay than elsewhere. *Fourth*, once the barrier island system had been developed, oyster reefs doubtless began to grow in lower Aransas and Mesquite bays.

The death and subsequent burial of oyster reefs throughout the area can be attributed to a variety of causes. In Copano and San Antonio bays an occasional prolonged influx of fresh water may have killed the reef organisms; in lower Aransas and Mesquite bays prolonged exposure to high salinity accompanying extended periods of low rainfall might have been responsible. Sand or mud deposited on reefs during unusual storms may have accounted for the death of reef-building animals on still other reefs.

## CONCLUSIONS

Numerous buried shell reefs in the bays of the Rockport, Texas, area do not appear to be significantly different in size and shape from living reefs. Buried reefs have been found in areas no longer supporting reefs. This is believed to be due to either too high or too low salinities or to burial by sediments. It is believed unlikely that the buried reefs could have grown during the post-

Pleistocene rise in sea-level because of the probability that the bays would have lacked barrier islands at their mouths which in turn develop the brackish water conditions essential to oyster growth. Therefore, oyster reefs 14 feet or more below the bottom of modern bays suggest that the bays were somewhat deeper at the end of the Pleistocene and that they have since been largely filled by sediments carried in by rivers.

## REFERENCES

Collier, Albert, and Hedgpeth, J. W., 1950, An introduction to the hydrography of the tidal waters of Texas: Pub. Inst. Marine Science, vol. 1, pp. 123–194.

Galtsoff, P. S., 1931, Survey of the oyster bottoms in Texas: U. S. Bureau of Fisheries Investigational Report no. 6, pp. 1–30, 2 maps.

——, 1941, Oyster industry and problems of management of public oyster reefs in Texas: Texas Game, Fish and Oyster Commission, Coastal Division, Corpus Christi, April 10, 1941, 6 pp. mimeo.

Grave, Caswell, 1905, Investigations for the promotion of the oyster industry of North Carolina: Report, U. S. Commissioner of Fish and Fisheries for 1903, pp. 247–341.

Moore, H. F., 1907, Survey of oyster bottoms in Matagorda Bay, Texas: Report, U. S. Commissioner of Fish and Fisheries and Special Papers for 1905, Bureau of Fisheries document no. 610, 86 pp., 13 pls., 1 map.

Price, W. Armstrong, 1933, Role of diastrophism in topography of Corpus Christi area, south Texas: Bull. Am. Assoc. Petroleum Geologists, vol. 17, pp. 907–962.

——, 1947, Equilibrium of form and forces in tidal basins of coast of Texas and Louisiana: Bull. Am. Assoc. Petroleum Geologists, vol. 31, pp. 1619–1663.

Richards, Horace G., 1939, Marine Pleistocene of Texas: Bull. Geol. Soc. America, vol. 50, pp. 1885–1898.

Zeuner, Frederick E., 1945, The Pleistocene period, its climate, chronology and faunal successions: London, The Ray Society, pp. 1–322.

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# SMALL TSUNAMI WAVES REACHING CALIFORNIA FROM THE JAPANESE EARTHQUAKE OF MARCH 4, 1952*

By WALTER H. MUNK

TSUNAMI waves from the Japanese earthquake of March 4, 1952, have been recorded on the "tsunami recorders" at La Jolla and Oceanside, California (fig. 1).

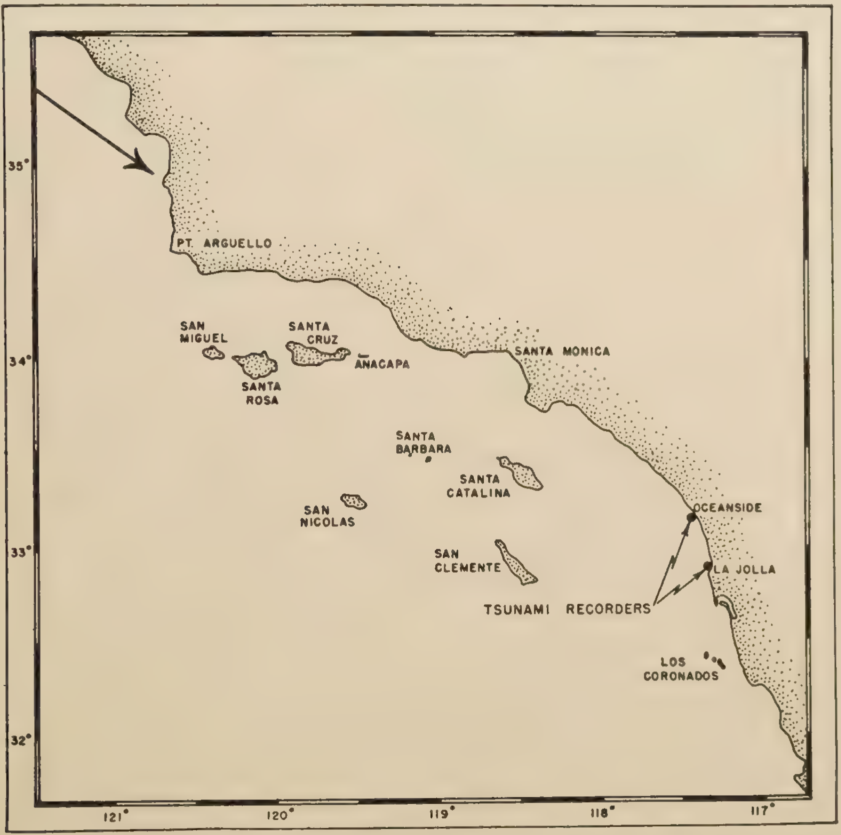
35°
34°
33°
32°
121°
120°
119°
118°
117°
PT. ARGUELLO
SAN MIGUEL
SANTA CRUZ
ANACAPA
SANTA ROSA
SANTA MONICA
SANTA BARBARA
SANTA CATALINA
SAN NICOLAS
OCEANSIDE
SAN CLEMENTE
LA JOLLA
TSUNAMI RECORDERS
LOS CORONADOS

Fig. 1. Location of tsunami recorders. The large arrow shows the direction of arrival along a great-circle route.

The instruments[1] suppress by means of hydraulic and pneumatic filters the ocean swell and tides, and are most sensitive to waves of periods from 10 minutes to 3 hours (table 1). The signal at Oceanside is transmitted by radio link to La Jolla, where it is recorded simultaneously with the La Jolla signal on a "Speedomax" multichannel recorder.

The early part of the record (fig. 2) consists of irregular fluctuations with periods of the order of 10 minutes, and actual amplitudes of about 1 inch. There is no coherence between the fluctuations at La Jolla and Oceanside. These fluctuations

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* The work on long-period ocean waves is supported by the Office of Naval Research, under contract with the University of California. Manuscript received for publication May 9, 1952.

[1] W. H. Munk, H. V. Iglesias, and T. R. Folsom, "An Instrument for Recording Ultra Low Frequency Ocean Waves," *Rev. Scient. Instr.*, 19:654–658 (1948).

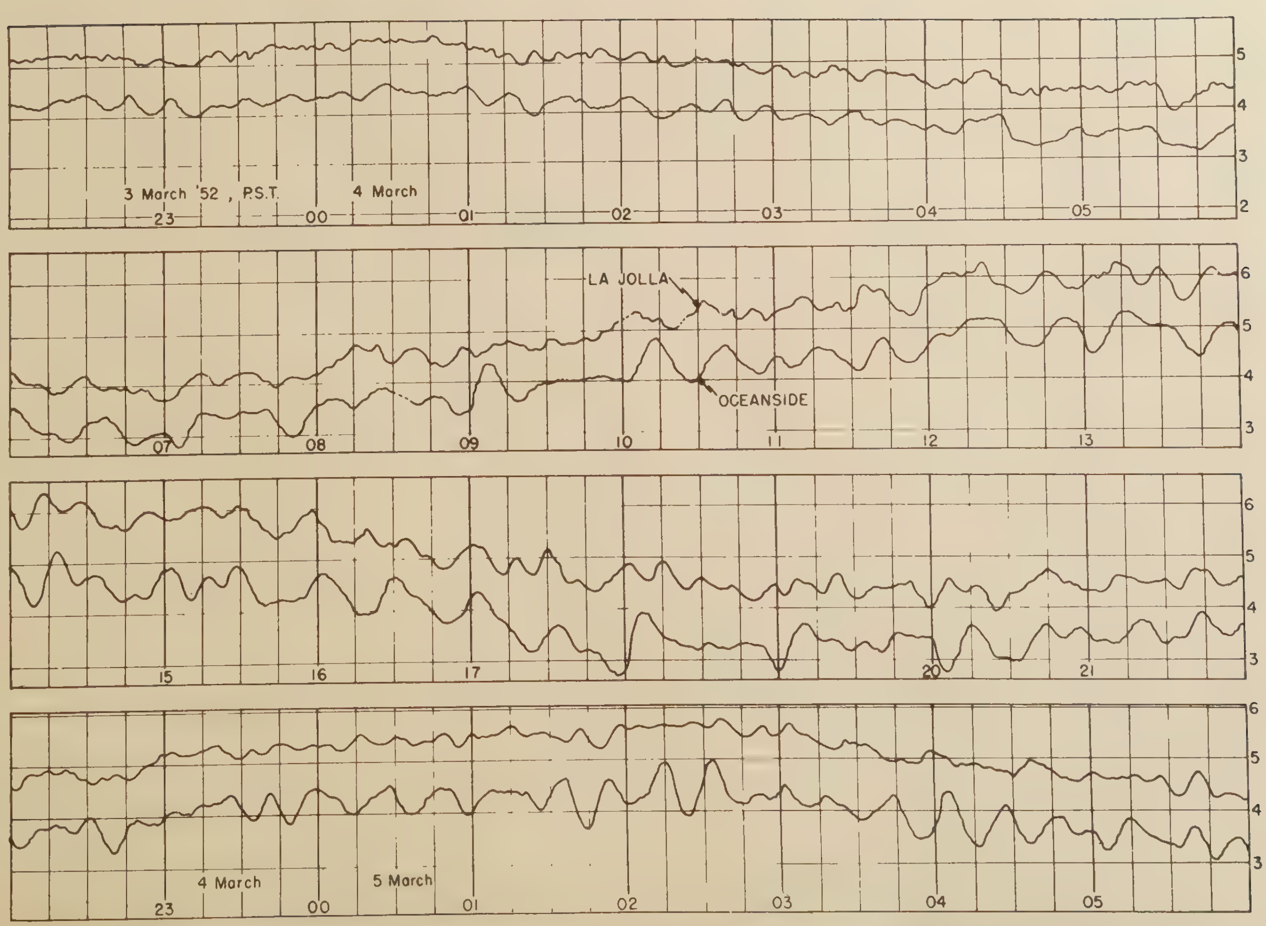

Fig. 2. Simultaneous records of Japanese tsunami at La Jolla and Oceanside, California. The numbers to the right give the recorded amplitude in inches. Actual amplitudes can be estimated from table 1.

are caused by meteorologic conditions, and they represent typical background in this part of the spectrum of ocean waves.

The computed arrival time[2] is 4 March, 0400 ± 30 min. PST. Starting at 0430 there is some indication of an arrival of a long-period disturbance, but not until 1000 is the disturbance above background. The largest waves occur between 1400 and 1800. The period is somewhat longer than 30 minutes. This is unusually long for tsunamis. The amplitude is about 1.5 inches at Oceanside, about 1 inch at La Jolla. There is some coherence between the two records, with similar phases occurring at Oceanside 2 to 3 minutes after La Jolla. This is surprising, because Oceanside is nearer to the epicenter. Possibly the waves have traveled round the south side of San Clemente Island (fig. 1), but even so, a time delay of two minutes is difficult to account for. The time delay is not instrumental. One possible explanation is that in the ocean basin between the mainland and the islands some complex oscillation is excited by the tsunami, and that it is characteristic of this oscillation that high and low water occur earlier at La Jolla than at Oceanside.

TABLE 1

RATIO OF RECORDED TO ACTUAL AMPLITUDE FOR STATED PERIODS

| | Swell | | Tsunamis | | | Tides |
|---|---|---|---|---|---|---|
| Period | $10^s$ | $1^m$ | $10^m$ | $45^m$ | $3^h$ | $12^h$ |
| Response ratio | .0003 | 0.01 | 0.29 | 0.55 | 0.32 | 0.07 |

After 2000 there is no apparent coherence, and the periods are shorter. It cannot be decided to what extent this part of the record represents a later stage in the tsunami, or background from meteorologic factors.

A comparison with the Honolulu tide record is instructive.[3] The period of the waves at Honolulu is again somewhat larger than 30 minutes, the amplitude about 6 inches. Hence the amplitude at the California stations is 20 per cent of the amplitude at Hawaii. Only a very small part of the reduction can be ascribed to the greater distance of the California stations. Let $r = 10\frac{3}{4}^h/7\frac{1}{2}^h = 1.43$ designate the ratio of travel times. For one-dimensional wave propagation the corresponding amplitude ratio varies from $r^{-1/3} = 0.89$ near the wave front to $r^{-1/2} = 0.84$ in the body of the record.[4] For waves with cylindrical symmetry the corresponding ratios are $r^{-5/6} = 0.74$ and $r^{-1} = 0.70$. At all events, we should expect the amplitude in California to equal more than 0.70 of the amplitude at Hawaii, whereas the observed ratio is 0.20. For comparison, the observed ratio for the Aleutian tsunami of April 1, 1946, is about one-third.

One possible explanation is reflection from the continental shelf[5] off California. The depth over the shelf decreases from 10,000 feet to 3,000 feet in 15 statute miles, a distance corresponding to 15 per cent of the wave length at 3,000 feet depth. Th ratio in wave velocities is $s = \sqrt{3{,}000/10{,}000} = 0.55$. The coefficient of amplitud transmission[6] for an abrupt change in depth is

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[2] Velocity $\sqrt{gh}$ ($h$ is depth) along a great-circle route.

[3] I am indebted to the Director of the U. S. Coast and Geodetic Survey for making this record available at an early time.

[4] H. Jeffreys and B. S. Jeffreys, *Methods of Mathematical Physics*, 2d edition (Cambridge Univ. Press, 1950), p. 517.

[5] J. D. Cochrane and R. S. Arthur, "Reflection of Tsunamis," *Jour. Mar. Res.*, 7:239–251 (1948).

$$\frac{2\sqrt{s}\cos\theta_1}{\cos\theta_1 + s\cos\theta_2}$$

where $\theta_1$ is the angle of incidence, and $\sin\theta_2 = s\sin\theta_1$. For near grazing incidenc (see arrow on fig. 1), setting $\theta_1 = 70°, 80°$, and $85°$ yields transmission rates of 0.62 0.40, and 0.23. The third value corresponds roughly to observed conditions. Ar alternate hypothesis is that the bottom topography off Honolulu is better "tuned' to 30-minute tsunamis from the northwest than the topography off California.

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[6] The factor $\sqrt{s}$ in the numerator removes the amplitude increase due to shoaling, since thi effect applies equally to the Hawaii and California records.

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# SEDIMENTATION RATES IN TEXAS ESTUARIES AND LAGOONS[1]

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La Jolla, California

## ABSTRACT

Detailed unpublished soundings of Texas bays made by the United States Coast and Geodetic Survey in the last century have been compared with recent surveys. The depth changes appear to show a reasonable relation to river mouths and to the silt-load measurements of these rivers when taken in connection with tide-gauge data which suggest coastal sinking. The fill has occurred primarily as a general shoaling of the flat bay floors and secondarily as a direct encroachment of subaerial deltas onto the bays. So far as could be determined only two rivers, the Trinity and the Colorado of Texas, have extended their deltas appreciably since the time of the old surveys. An estimated average rate of bay shoaling of 1.26 feet per century comes from the compilation of 20,518 points of comparison. However, the "silt" load of Texas streams, which probably is deposited largely in the bays, is too high for this rate and suggests that there has been submergence. By allowing for submergence the amount of 1.8 feet which is the average relative sea-level rise per century for four Gulf Coast tide stations, a total estimated rate of sedimentation in the bays becomes 3 feet per century. This material, however, has a high water content and would make only about half as much sedimentary rock, depending on the degree of compaction.

## INTRODUCTION

A neglected method of studying rates of sedimentation is by a systematic comparison of the old and new detailed soundings of the United States Coast and Geodetic Survey. Soundings which can be used for this purpose extend back for more than 100 years, but effective results can be obtained only by the use of the original unpublished hydrographic survey sheets which include about ten times as many soundings as the published charts. Old surveys of the lagoons and estuaries[3] of the Texas coast (Fig. 1) have enormous detail, commonly 100 or more soundings per square mile, and are available on the same scale as the recent even more complete surveys extending from Corpus Christi to Galveston. As a result, an attempt to investigate sedimentation rates in these bays seemed desirable along with other sediment studies along the Gulf Coast being carried on in the American Petroleum Institute recent sediment project.[4] The depth changes discussed by Price (1947) provide an indication of the trend but were based on published charts and failed to obtain the complete picture available from the unpublished survey sheets. The comparison was made easier by the 7-foot average depth of the bays which allowed a high degree of accuracy of soundings. It was realized, however, that shoaling of bays gives only one indication of sedimentation

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 642. This investigation was supported by a grant from the American Petroleum Institute, Project 51. Manuscript received, February 4, 1953.

[2] Scripps Institute of Oceanography, University of California. The able assistance of D. B. Sayner, J. R. Moriarty, Elizabeth Sanborn, and Ruth Young in compiling the large mass of statistics on which the paper is based is gratefully acknowledged. Suggestions from D. L. Inman and P. C. Scruton of Scripps Institution and G. F. Jordan of the U. S. Coast and Geodetic Survey have also been of considerable help.

[3] Lagoons refer to the bays inside and parallel with barrier islands; estuaries refer to the bays deeply indenting the coast.

[4] An investigation of nearshore recent sediments in the northern Gulf of Mexico.

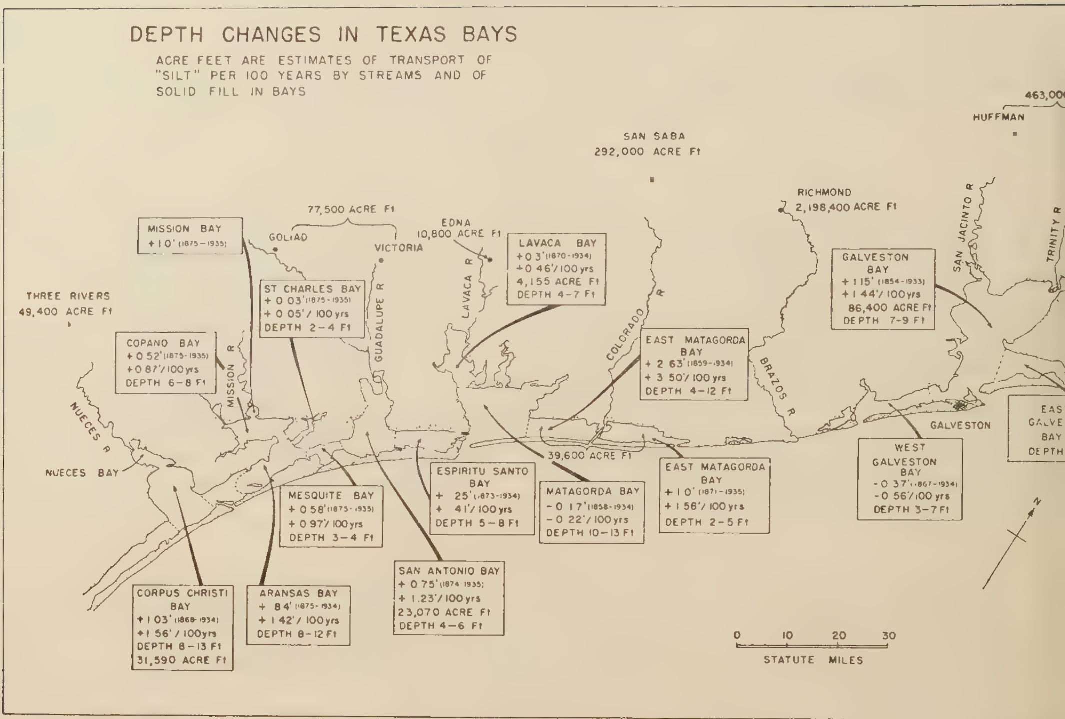
DEPTH CHANGES IN TEXAS BAYS
ACRE FEET ARE ESTIMATES OF TRANSPORT OF "SILT" PER 100 YEARS BY STREAMS AND OF SOLID FILL IN BAYS
463,00
HUFFMAN
SAN SABA
292,000 ACRE Ft
RICHMOND
2,198,400 ACRE Ft
77,500 ACRE Ft
EDNA
10,800 ACRE Ft
GOLIAD
VICTORIA
MISSION BAY
+ 1 0' (1875–1935)
LAVACA BAY
+ 0 3' (1870-1934)
+ 0 46'/100 yrs
4,155 ACRE Ft
DEPTH 4–7 Ft
SAN JACINTO R
TRINITY R
GALVESTON BAY
+ 1 15' (1854-1933)
+ 1 44'/100 yrs
86,400 ACRE Ft
DEPTH 7-9 Ft
THREE RIVERS
49,400 ACRE Ft
ST CHARLES BAY
+ 0 03' (1875-1935)
+ 0 05'/100 yrs
DEPTH 2–4 Ft
GUADALUPE R
LAVACA R
COLORADO R
COPANO BAY
+ 0 52' (1875-1935)
+ 0 87'/100 yrs
DEPTH 6–8 Ft
MISSION R
EAST MATAGORDA BAY
+ 2 63' (1859-1934)
+ 3 50'/100 yrs
DEPTH 4–12 Ft
BRAZOS R
NUECES R
GALVESTON
EAS
GALVE
BAY
DEPTH
NUECES BAY
39,600 ACRE Ft
ESPIRITU SANTO BAY
+ 25' (1873-1934)
+ 41'/100 yrs
DEPTH 5–8 Ft
MATAGORDA BAY
- 0 17' (1858-1934)
- 0 22'/100 yrs
DEPTH 10–13 Ft
EAST MATAGORDA BAY
+ 1 0' (1871-1935)
+ 1 56'/100 yrs
DEPTH 2–5 Ft
WEST GALVESTON BAY
- 0 37' (1867-1934)
- 0 56'/100 yrs
DEPTH 3–7 Ft
N
MESQUITE BAY
+ 0 58' (1875-1935)
+ 0 97'/100 yrs
DEPTH 3–4 Ft
SAN ANTONIO BAY
+ 0 75' (1874-1935)
+ 1.23'/100 yrs
23,070 ACRE Ft
DEPTH 4–6 Ft
CORPUS CHRISTI BAY
+ 1 03' (1868-1934)
+ 1 56'/100 yrs
DEPTH 8–13 Ft
31,590 ACRE Ft
ARANSAS BAY
+ 84' (1875-1934)
+ 1 42'/100 yrs
DEPTH 8-12 Ft
0 10 20 30
STATUTE MILES

FIG. 1.—Depth changes in Texas bays. Boxes contain (1) shoaling (+) or deepening (−) in feet since early (2) shoaling rate per century, (3) approximate number of acre-feet of solid sediment per century represented by t ing, and (4) depth of main parts of bay in feet. Acre-feet given in brackets for rivers represent 100 years at pres (Texas, 1952).

rate because changes of land and sea-level, compaction of sediment, and various other factors complicate the results. Despite these difficulties, the depth comparisons appear to be significant and can be related to silt-load studies of Texas rivers (Texas, 1952).

## METHODS

To compare charts prior to 1921 with new charts it was first necessary to make adjustments for the new latitude and longitude data established in 1927 (N.A. 1927 Datum). Further accuracy was added by superimposing reefs and shorelines. The many recognizable points and indentations of the shorelines of the Texas bays which are common to both the old and the new surveys were helpful in this connection. By use of a combination of reefs, shorelines, and corrected latitudes and longitudes, the old and new charts were superimposed on a tracing table and soundings of the two surveys were compared to develop the basis for isopleth depth-change diagrams. Slight difficulty in the undertaking arose from the use of soundings to the nearest quarter-foot on many of the old surveys whereas nothing smaller than a half-foot was used on the new. In order to obtain the greatest accuracy the comparison figures were given in quarter-feet wherever this information was available. It was recognized, however, that such small differences are far greater than the range of accuracy of soundings obtained for navigational purposes even in the very shallow bays under consideration. Despite the use by the surveyors of tide gauges to correct for sea-level differences during their operations, errors result from the sea-levels being somewhat different on one side of a bay than on the other, a condition commonly developed during periods of strong winds. Furthermore, some small errors in positions or in measuring the depths and even in recording these measurements must be expected. In observing and correcting the soundings for vertical datum, round values are in general less than the absolute true depths—a cartographic practice which precludes charting of soundings greater than true depths. However, the possibility of the sounding pole or lead sinking into soft bottom can not be overlooked. As a result, the individual comparisons should not be given much weight, whereas good results can come from noting the average depths in small areas of the old survey and comparing these with average depths in the same areas on the new surveys.

A total of 20,518 comparisons in about 1,000 square miles of bay floor was noted on the large-scale charts, and isopleth contours were drawn after considerable averaging of the depth-change notations. In order to further reduce the errors the contours were drawn only to the nearest foot. The average change in depth for individual bays, however, has been computed on the basis of all of the chart difference notations (Fig. 1).

The reliability of these methods is strongly supported by the relation between shoaling and river sources of sediment. Examination of the depth-change maps (Figs. 2–5) shows that no random errors of depth could produce these relations if the bay depths had remained static. Furthermore, the amount of change is so consistent over large areas of virtually horizontal bottom that they are not explicable by errors in survey methods. Where these consistent changes are of the order of one foot or more there can be little doubt that a change has actually occurred. On the other hand, many of the minor details of the maps should be considered as subject to some doubt.

### CORPUS CHRISTI BAY (FIG. 2)

Corpus Christi Bay is the deepest bay along the Texas coast. Aside from the shoal upper part, Nueces Bay, the depths are mostly more than 10 feet and about half of the main bay has a flat bottom between 12 and 14 feet deep. There is only a narrow belt between the shore and the 10-foot contour.

The depth changes in Figure 2 are based on comparison of surveys in 1868 and 1934. The net change is a shoaling of 1.03 feet in the 66-year period, or 1.56 feet per century. Of the 2,156 comparison notations in Corpus Christi Bay, only about 3 per cent indicate deepening.

The chief source of sediment for the bay is the Nueces River (Fig. 1). Judged from the Three Rivers Station, this river carries about 750,000 tons of sediment

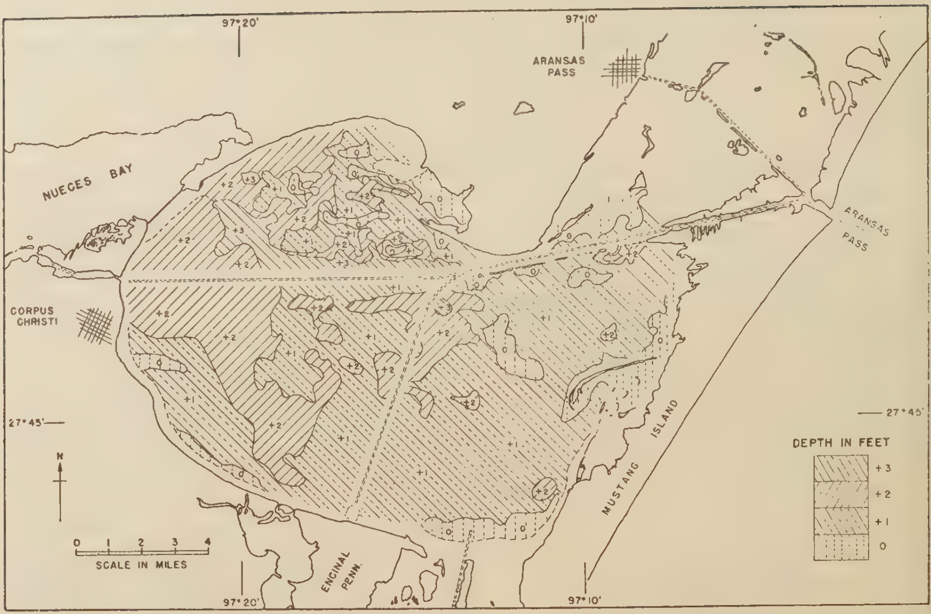

Fig. 2.—Corpus Christi Bay showing depth changes between 1868 and 1934. Pairs of parallel dashed lines indicate ship channels which have been dredged to main ports.

a year. Because of a dam on the lower river this sediment ceased to be important in 1930. The main delta has not been extended appreciably into Nueces Bay since 1868, but the shallow cove north of the delta has prograded about one mile. The effect of the Nueces River on Corpus Christi Bay seems very evident since the upper half or western part has filled an average of about 2 feet in 66 years. This fill decreases toward the barrier, Mustang Island. Minor sources of sediment came from the erosion of the bluffs on the west side of the bay, from hurricane overwashes into the bay from the barrier island, and from wind-blown sand. Contrary to Price and Gunter (1942), the fill in the bay does not appear to grade away from the ship channels so that the spoil dumps appear not to have been a very important source. Recent soundings of dumps which had previously been submerged show no appreciable change in their contour. The irregularities of fill indicated in the northern area are somewhat puzzling. In general this zone has had less fill than the part outside the city of Corpus Christi. This difference may be due in part to artificial conditions set up by the drainage from the city.

### BAYS BETWEEN ARANSAS AND CAVALLO PASSES (FIG. 3)

The bays lying inside St. Joseph and Mustang islands are a combination of lagoons and estuaries. For the most part they are very shallow so that they can be traversed only in small, shallow-draft boats. The deepest of them, Aransas Bay, is somewhat comparable with Corpus Christi Bay in that the water deepens

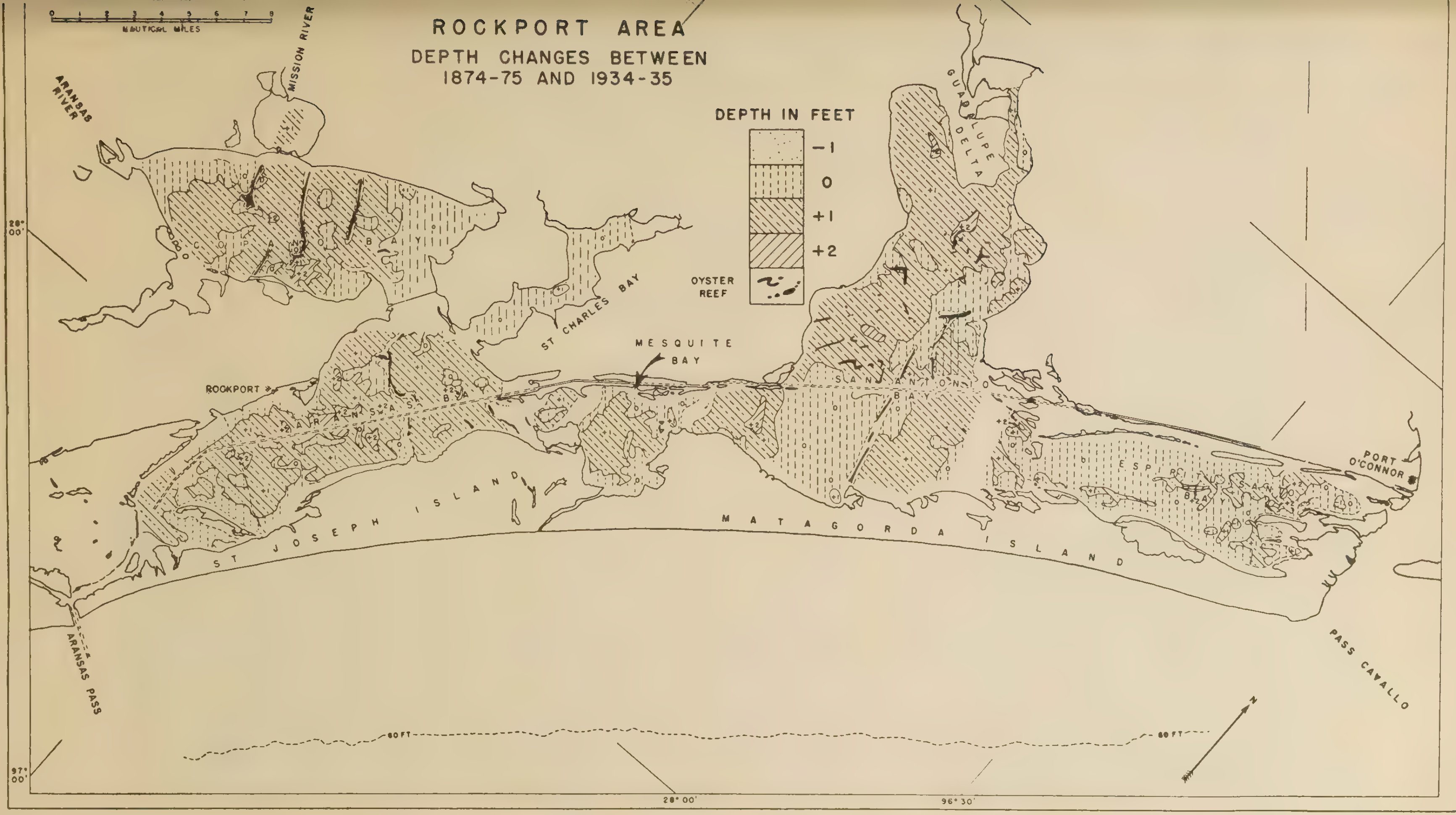
ROCKPORT AREA
DEPTH CHANGES BETWEEN
1874-75 AND 1934-35
DEPTH IN FEET
−1
0
+1
+2
OYSTER REEF
0 1 2 3 4 5 6 7 8
NAUTICAL MILES
ARANSAS RIVER
MISSION RIVER
COPANO BAY
ST CHARLES BAY
MESQUITE BAY
ROCKPORT
ARANSAS BAY
SAN ANTONIO BAY
GUADALUPE DELTA
ESPIRITU SANTO BAY
PORT O'CONNOR
ST JOSEPH ISLAND
MATAGORDA ISLAND
ARANSAS PASS
PASS CAVALLO
60 FT
N
28° 00'
97° 00'
28° 00'
96° 30'

FIG. 3.—Bays between Aransas Pass and Pass Cavallo showing depth changes between 1874 and 1935.

in a short distance from the shore and most of the floor is monotonously flat, with depths of 8–12 feet. Shoaling is somewhat variable, averaging 0.84 foot in 59 years, or 1.42 feet per century. Only 3 per cent of the 901 comparison notations show a cut as was the case in Corpus Christi Bay. There does not appear to be any noticeable trend in the direction of fill. Much of the irregularity of the isopleths may be due to errors in the methods.

Copano Bay is approximately the same size as Aransas but differs from it in the much larger number of submerged oyster reefs which traverse it normal to its length. Aside from the reefs, the depths of the floor run rather consistently between 6 and 8 feet. Copano Bay has filled an average of 0.52 foot in 60 years, or 0.87 foot per century. Presumably the chief source of sediment for the bay comes from the Mission and Aransas rivers. The relation of fill to these rivers is not clear, however, especially as there appears to have been no fill directly off the small bay at Aransas River. On the other hand, both Mission Bay and the area outside have had a fairly consistent one-foot fill. The northeast end of the bay farthest from the rivers shows virtually no change in depth. It is noticeable that the shallow near-by estuary, St. Charles Bay, which receives no appreciable drainage has had an average shoaling of only 0.03 foot. Another large source of sediment in Copano Bay is the débris from the oyster reefs.[5] In the inter-reef zones a common shell content is 30 per cent.

Mesquite Bay is very shallow, mostly 3–4 feet deep, and most of the floor is very flat. Unlike St. Charles Bay, more than half of its area has undergone a definite fill and the net fill was 0.58 foot in 60 years (0.97 foot per century). Oyster reefs are found only along the margins of the bay. There may be a source of sediment from San Antonio Bay since during "northers" currents flow strongly into Mesquite Bay from the northeast. Another source of sediment for the bay is the intermittent north flow through Cedar Bayou, an inlet, which gives discontinuous access to the open ocean. Cedar Bayou decreased in depth about 5 feet in the 60 years between surveys. Sand blown from the sand dunes of the barrier island may be an important additional source of sediment.

San Antonio Bay, which has a long arm extending up to the Guadalupe Delta, is a shallow bay having depths which range mostly from 4 to 6 feet in the main bay and are mostly not more than 1–2 feet in the small bays around the delta. The main source of sediment is the Guadalupe River, a combination of the San Antonio and Guadalupe rivers, which together carry about 1,200,000 tons of sediment a year (Texas, 1952). One of the curious things about the delta of the Guadalupe is that its outline has changed only a very slight amount since the survey in 1875. On the other hand, the small bay north of the delta has been partly filled during this interval and Green Lake, a few miles north, may receive considerable sediment during floods. Depths in most of San Antonio Bay have shoaled, with an average decrease of 0.76 foot in 61 years, or 1.23 feet per 100 years. Of the 1,171 comparison notations only about 3 per cent indicate deepening. The greatest shoaling has occurred in the upper bay. It is notable that there has been much less shoaling on the east side in the central bay whereas in the lower bay the shoaling has been less on the west side.

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[5] Little attempt was made to compare the depth changes of the reefs in the interim between surveys because of the irregularity of surface.

Espiritu Santo Bay is somewhat deeper than San Antonio, most of its floor lying between 5 and 8 feet below sea-level. There are extensive shoals at both ends of this bay. The large shoal and the islands on the northeast are evidently a tidal delta due to material coming from Cavallo Pass. The depths have been constant in Espiritu Santo Bay although there is a small zone near the tidal delta where shoaling of 1 or 2 feet has taken place. No important stream empties into this bay. Most of the southwestern part of the bay has shown no change. The average for the entire bay is a decrease in depth of 0.25 foot. It is interesting, however, to note that this bay, unlike all the others on the southeast, has a rather considerable area, constituting 28 per cent of the 905 notations, where slight deepening has occurred.

### MATAGORDA BAY (FIG. 4)

Matagorda Bay is cut off from the open Gulf by Matagorda Peninsula, a group of barrier islands with only narrow gaps. It is a relatively deep bay, the main part being mostly 10–13 feet deep, almost the same as Corpus Christi Bay, although the various arms give Matagorda Bay a shoaler average depth. The shallow eastern lagoon has been segmented by the recent growth of the Colorado Delta across the lagoon. West of the delta the water deepens progressively to 13 feet south of Point Palacios. Lavaca Bay, an estuary on the northwest, has depths ranging around 4 to 7 feet.

The main part of the bay has no large entering river, but Lavaca Bay has a source of sediment in the Lavaca River which carries about 160,000 tons of sediment (Texas, 1952), and East Bay had a much larger source from the Colorado of Texas River to 1936 when most of the Colorado drainage was diverted into the open ocean through a canal cut across Matagorda Peninsula. The "silt" load in the Colorado at San Saba is given as 4,452,084 tons a year (Texas, 1952). Prior to 1926 sedimentation at the mouth of the Colorado was greatly impeded by a log jam in the lower part of the river which caused flooding and spreading of sediment over the lowlands. However, between 1926 and 1930 the jam was removed and the channel opened. As a result, the Colorado built a delta across East Bay a distance of 4 miles in about 6 years. A very obvious relation of entering rivers to shoaling is found in East Bay where an average depth change has amounted to 2.63 feet in 75 years,[6] or 3.5 feet per 100 years west and 1.0 foot in 64 years or 1.56 feet per century east of the delta. About 10 or 15 per cent of this lagoon has had changes of as much as 5 or 6 feet and only about 1 per cent of the 2,048 notations shows deepening. This fill includes the delta itself which was built out into a bay which was 5 feet deep in 1859. As shown by the depth changes, the sediment from

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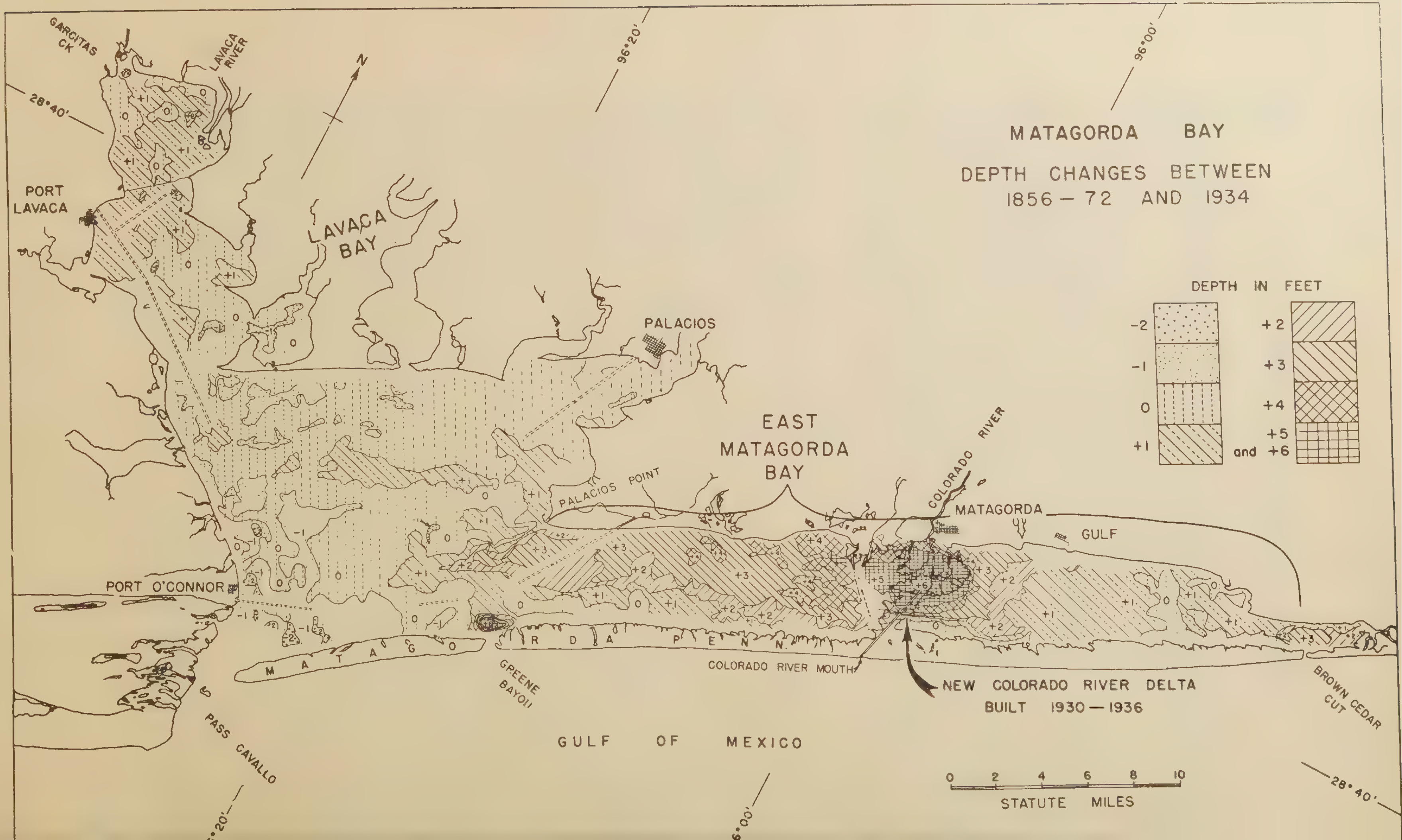
[6] Actually the fill may have occurred principally during the building of the Colorado Delta.



MATAGORDA BAY

DEPTH CHANGES BETWEEN
1856 — 72 AND 1934

DEPTH IN FEET
-2
-1
0
+1
+2
+3
+4
+5 and +6
GARCITAS CK
LAVACA RIVER
28°40'
96°20'
96°00'
N
PORT LAVACA
LAVACA BAY
PALACIOS
EAST MATAGORDA BAY
PALACIOS POINT
COLORADO RIVER
MATAGORDA
GULF
PORT O'CONNOR
MATAGORDA PENN.
GREENE BAYOU
COLORADO RIVER MOUTH
NEW COLORADO RIVER DELTA BUILT 1930 — 1936
BROWN CEDAR CUT
PASS CAVALLO
GULF OF MEXICO
0 2 4 6 8 10
STATUTE MILES

the Colorado River has been carried west far more than east, presumably due to the prevailing east winds. Also the shoaling is far greater on the north side of the lagoon than on the south. A zone where the depths have decreased by 3 feet extends somewhat west of Point Palacios, a distance of about 20 miles from the emerged part of the Colorado Delta. On the east, however, the zone of 3-foot fill does not extend more than 2 miles from the delta front.

The main bay is unique relative to depth changes in that it has actually deepened more than it has shoaled, the net change being a sinking of 0.17 foot in 76 years (0.23 foot per century).[7] The deepening has taken place especially on the west side of the bay which is farther from the influence of the sediment coming out of the Colorado River. Of the 2,560 notations, about 60 per cent indicate deepening. The largest deepening has occurred near Cavallo Pass, suggesting possible tidal action. It is interesting that the areas with unchanged depths extend well up through Lavaca Bay and only small fill has occurred at the mouth of the Lavaca River. The delta of this river has not been appreciably extended since 1870 so far as can be ascertained from the two surveys.[8]

Small zones of fill are seen inside the two inlets, Greene Bayou and Brown Cedar Cut. At these places tidal deltas have been built by the inflowing currents. It should be noted that the exact shape of these tidal deltas is not indicated by the isopleth contours which are generalized.

Although the main bay has shown a slight net deepening, the addition of the notations from Lavaca and East Bay to the notations of the main bay shows an average shoaling (for all notations) of 0.45 foot. Also, so far as volume is concerned the thickness of the fill in East Bay far outbalances the deepening in the main bay.

### GALVESTON BAY (FIG. 5)

Galveston Bay has the largest estuary along the Texas coast. This bay is protected from the open Gulf by Galveston Island and Bolivar Peninsula. It has two lagoonal arms, West Bay being nearly separate from the main bay whereas East Bay is closely connected with the main bay, although partly separated by oyster reefs. Another oyster reef partly divides the lower and upper bays, extending discontinuously between Smith Point and Edwards Point. The upper bay has two heads, one extending to the delta of the Trinity River and the other to the drowned mouth of the San Jacinto River. Trinity River is one of the large rivers of Texas, carrying more than 6 million tons of sediment a year (Texas, 1952). The San Jacinto, a much smaller river with a drowned mouth, is not as important a source of sediment but carries about 830,000 tons a year. Drainage from the city of Houston, which is located along an estuary branch of this river, must provide

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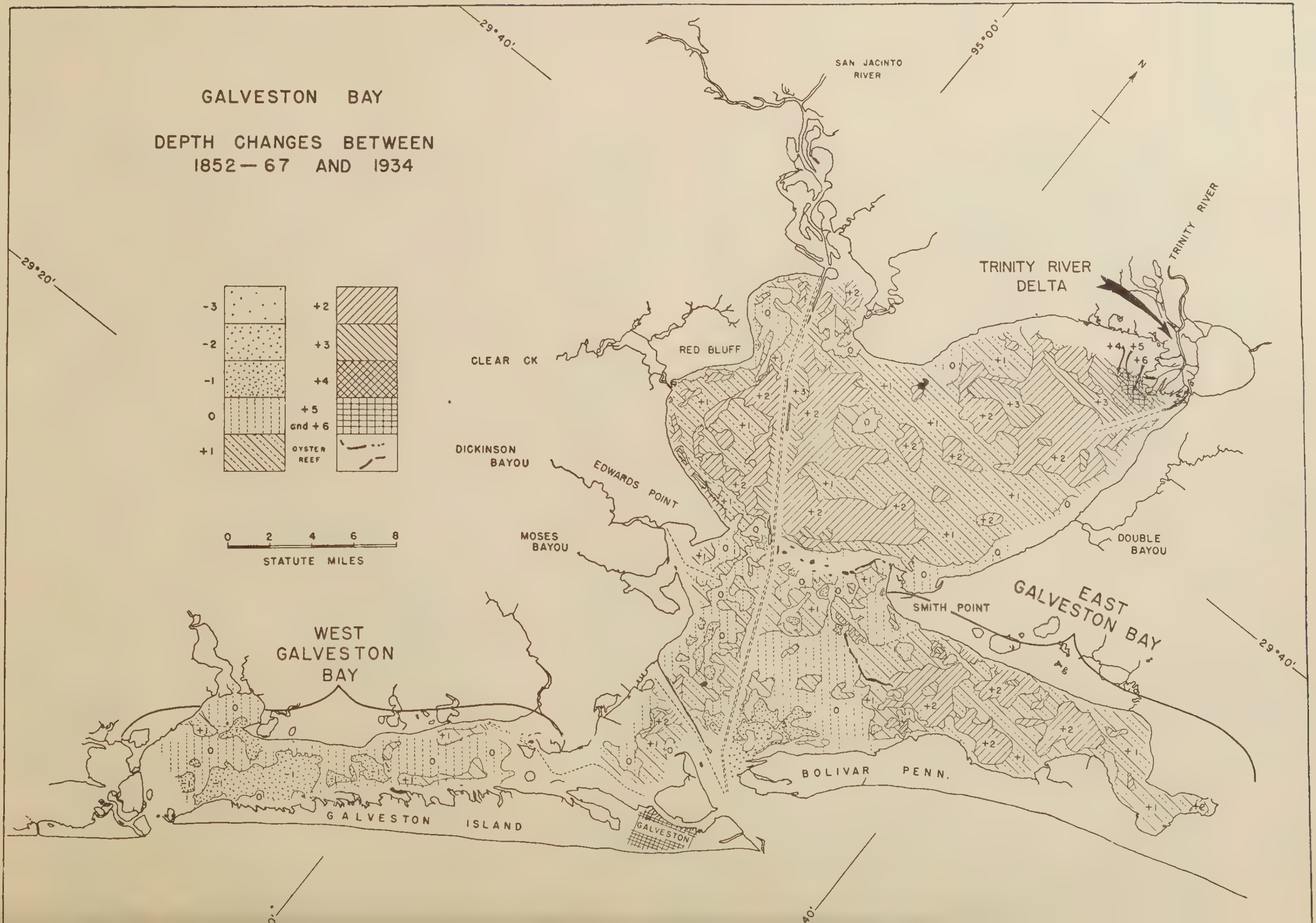
[7] Price (1947) showed soundings from a Spanish chart of 1689 which gave depths of 2 brazas (about 11 feet) for the main bay but these units are too large and the 5 soundings too few to give this evidence much significance.

[8] The Cardenas map made in 1690 (Price, 1947) may possibly confirm this point, but it is obviously not an accurate survey.



GALVESTON BAY

DEPTH CHANGES BETWEEN 1852—67 AND 1934

-3
-2
-1
0
+1
+2
+3
+4
+5 and +6
OYSTER REEF
0
2
4
6
8
STATUTE MILES
29°40'
95°00'
29°20'
29°40'
N
SAN JACINTO RIVER
TRINITY RIVER
TRINITY RIVER DELTA
RED BLUFF
CLEAR CK
DICKINSON BAYOU
EDWARDS POINT
MOSES BAYOU
DOUBLE BAYOU
SMITH POINT
EAST GALVESTON BAY
WEST GALVESTON BAY
BOLIVAR PENN.
GALVESTON ISLAND
GALVESTON

considerable sediment. Another source comes from the erosion of the low bluffs on the northwest side of the Bay. According to the United States Engineers (1935), the cliffs near Red Bluff are retreating at a rate of 6½ feet per year. Galveston Bay has also been influenced by a considerable amount of dredging during the development of the deep boat channels. The jetties built at the entrance to the bay by confining the tidal flow must have had additional effect.

In depth, Galveston Bay is intermediate between the other bays. The main bay, aside from the irregularities produced by the channels and the spoil dump, has a bottom that varies mostly from 7 to 9 feet. There is little difference in depth between the upper and lower parts of this bay, except for the deep cuts found near the bay entrance, which apparently are due to tidal action. In the inlet, a depth of 44 feet is found in the narrows. Both East Bay and West Bay are shallow, depths being mostly between 3 and 7 feet. These bays have no appreciable entering stream and no sign of a significant delta. An appreciable amount of sediment, however, may come into East Bay from the main bay through the gaps in the oyster reefs.

The depth-change map shows a general agreement between shoaling and sediment sources. Off the Trinity Delta, which has been extended about 0.3 mile into the bay since 1855, the depths have decreased markedly as is the case off the Colorado Delta in East Matagorda Bay. Away from the delta, the shoaling decreases southwest somewhat irregularly. Most of the upper bay has shoaled as much as 2 feet but there is a large area in the lower bay where no appreciable fill has occurred and near the entrance there has been deepening which presumably is related to the concentrated flow into the bay, which may have been accentuated by the jetties at the entrance. Along the west side of the bay the fill and cut appear to be irregular and may be partly the result of artificial changes. The average change for the bay is a fill of 1.15 feet in about 80 years, or 1.44 feet per century. About 7 per cent of the 6,200 notations indicate deepening. There are a few areas of shoaling running parallel with the west shore, bordered along the coast by an area of slight deepening or no change. This zonation could be explained by the wave erosion around Red Bluff, the inner part having been eroded, deposition having been farther out.

The west half of West Bay has deepened about 1 foot whereas there has been no appreciable change in the east half of the same lagoon. The total change in this arm is a deepening of 0.37 foot in 67 years (0.56 foot per century), which is the highest rate of deepening of all of the bays measured. About 70 per cent of the comparison notations show this deepening. It seems likely that the deepening in West Bay is the result of slow deposition which has been more than offset by a general sinking during the interval between surveys. The series of estuaries on the north side of Galveston Island may be a further indication of local sinking. The smoothly curving coast on the north side of Bolivar Peninsula is probably the result of old overwash fans which have not been submerged.

### COMPARISON WITH OTHER GULF COAST BAYS

The depth changes of other bays along the Gulf Coast have not been investigated except superficially. South of Corpus Christi, Laguna Madre is so shallow that most of it has not been included in the coastal surveys and no data comparing old surveys have been located. According to Price and Gunter (1942) this lagoon has been filling and large parts of it have become essentially tidal flats during the last half-century. While flying over the lagoon, it is almost impossible to tell where the land ends and water begins. The boundaries between land and water are said to change rapidly according to the strength and direction of the wind.

Mobile Bay has surveys extending back to 1849 but no isopleth map of changes has been made. A brief examination of the old and new charts suggests that the bay has had extensive shoaling amounting to between about 1½ and 3 feet. One curious thing about the comparison is that there appears to be less fill near where the delta has been actively building forward and more fill (almost 3 feet) near the entrance to the bay. It seems likely that Mobile Bay has filled more than any of the Texas bays except the east branch of Matagorda Bay. Mobile Bay indents the coast more deeply than any of the Texas bays and is receiving sediment from the Mobile River, a much larger river than any of those in Texas. The Mobile River has advanced the natural levees of its delta about a mile since 1849, compared with the 4 miles of delta growth of the Colorado of Texas which occurred in 6 years. The Mississippi has built as much as 1,000 feet a year into the shallow parts of the open Gulf and its diverted branch, the Atchafalaya, is filling Grand Lake at a very rapid rate, as much as 10 miles of delta extension in 7–8 years. The changes in the Mississippi Delta area will be considered in another article.

### SIGNIFICANCE OF DEPTH CHANGES

The preceding discussion of the Texas bays assumes that fill has taken place over almost the entire area. An average of the 20,518 depth-change observations of all of the Texas bays shows a net fill of 0.82 foot in about 65 years, or 1.26 feet per century. Many of the depth changes are readily understandable but others are of uncertain cause. Among the former can be included the great shoaling of East Matagorda Bay, where the delta of the large Colorado of Texas was built 4 miles across the lagoon, dividing it into two segments. The depth changes in the lagoon show clearly that deposition is occurring well beyond the margin of the emerged part of the delta. Similarly, the fill in the Trinity Bay arm of Galveston Bay is clearly related to the 0.3-mile advance of the Trinity Delta and here also the charts show active fill beyond the delta margin. The fill off other smaller rivers where deltas are not actively building forward, such as the Nueces, the Guadalupe, the Lavaca, the Aransas, and the San Jacinto, is more widespread although the bays seem to have had somewhat more fill in the vicinity of these river mouths than elsewhere. The more rapid rates of shoaling in Galveston, Corpus Christi, and San Antonio bays than in Matagorda and Copano bays are in line with the smaller sediment load being carried into the last two.

The parts of the bays which have been definitely deepened are partly near the openings in the barriers where the inlets have relatively strong currents due to tides or wind. The cuts in these places evidently can be related to tidal erosion. Elsewhere, slight deepening along the length of the barrier islands, the important deepening in the west arm of Galveston Bay, and the minor deepening in the main Matagorda Bay seem more reasonably explained by a rate of deposition which is so slow that it does not compensate for the submergence of the area. There may be some relationship between the shape of the shoreline on the inside of some barrier islands and the depth changes. In general, barrier islands having extensive estuaries along their inner margins are bordered by a bay floor where slight deepening has occurred whereas the smoother shorelines are more commonly bordered by zones having undergone shoaling. It is possible that the greater fill in Aransas Bay than in other bays which are nearer a sediment source may be due to this area having undergone less downwarping than the others.

## SEDIMENTATION IN RELATION TO DEPTH CHANGES

In considering the shoaling of the bays in relation to sedimentation, it is important to make allowances for two factors: one is level changes including sea-level and the other is the water content of the sediment. Considering first the changes indicated by tide gauges (Marmer, 1952), Galveston alone on the Texas coast has a long enough record to provide reliable information. Between 1909 and 1950, the sea has changed in relation to the land to the amount of approximately 1.0 foot (2.44 feet per century).[9] There are only three other stations available in the northern Gulf of Mexico where records have continued long enough for comparison. These all show a relative submergence as follows: at Pensacola, Florida, 0.53 foot between 1924 and 1950 (2.04 feet per century); at Cedar Keys, Florida, 0.42 foot between 1915 and 1950 (1.20 feet per century); and at Key West, Florida, 0.41 foot between 1912 and 1950 (0.85 foot per century). Since these changes are smaller than Galveston and since the Gulf Coast average changes of 1.63 feet per century are larger than the average for the rest of the world, 0.4 foot per century (Gutenberg, 1941),[10] it seems likely that the Gulf Coast is subsiding and that Galveston is subsiding at an exceptionally rapid rate. In fact, Gutenberg (1941) gives no more rapid rate for any tide station in the world. On the other hand, the shoaling in Galveston Bay is not very different from that in most of the other Texas bays nor is the shape of the bay distinctive. Therefore, the Galveston tide station may be representative of the rest of the Texas coast.[11] A more conservative estimate, however, comes from assuming that the Texas coast in general has undergone a change comparable with the average for the four northern Gulf stations. Under such an assumption the coast has submerged in relation to sea-level to the amount of 1.7 feet during the past century.[12] If this assumption is valid, the sedimentation rates per century are increased from 1.26 feet to approximately 3 feet. On the other hand, there is a surprising lack of historical evidence of coastal submergence. It has been suggested that subsidence at this rate since the time of early coastal charting would have submerged extensive tracts of those parts of the Gulf Coast which have seaward slopes as low as ½ foot per mile. Since large encroachments of the sea, except around parts of the Mississippi Delta, have not been found, it must be concluded either that these low-gradient areas have not sunk or that some form of deposition is building them up at a rate equal to the subsidence. A third alternative in some areas may be that subsidence has recently brought them close to sea-level without great encroachment because the lower part, now submerged, had a higher gradient. In any case, it is evident that this should be given further investigation.

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[9] Figures obtained from a diagram by Marmer (1952). This surprising rate is well documented by a network of bench marks which have been resurveyed repeatedly.

[10] The data for many areas outside the United States may be unreliable so that this average is of doubtful validity.

[11] A few years of records at Port Isabel (near the Mexico border) appears to show a trend similar to Galveston (H. A. Marmer, personal communication).

The typical sediments of the bays under consideration are a mixture of sand, silt, and clay. At the heads of the bays and especially near the rivers, the clay content of the sediments is very high whereas the sand content is high near the barrier islands, especially where there have been overwashes and where tidal deltas have been built into the bays. Based on the extensive analyses of sediments in the area extending from Aransas Bay to San Antonio Bay (made in connection with American Petroleum Institute Project 51), an average bay sediment can be said to consist approximately of the following: 40 per cent clay, 30 per cent silt, and 30 per cent sand. The typical water content of such sediment is about 70 per cent by volume. This means that the material accumulating on the bay floor has a larger percentage of water than of solid sediment. If the pore space were reduced to about 20 per cent, which is the approximate pore space of rock of this composition, the 3 feet would become 1.5 feet of future rock per century for the Texas bays. On the other hand, the Tertiary Gulf Coast sediments of this type have a much higher water content, perhaps 30 per cent, which would make the rate 1.8 feet per century. All these estimates are speculative but they may be of the right order. The influence of agriculture may have made the rate too high so far as pre-historical records are concerned, but conservation effects of man may have somewhat balanced the excessive soil erosion.

## SHOALING IN RELATION TO RIVER SEDIMENT

The recent Government report of "silt" content of Texas rivers (Texas, 1952) provides an interesting comparison with the rate of bay shoaling. Table I summarizes the data from what appear to be the most significant stations. It may be seen that there is a rough correlation between the decreased volume of water in the bays and the "silt" load[13] determined for river stations at points averaging about 25 miles from the river mouths.

[12] According to Gutenberg, 0.4 foot (10 cm.) per century represents a sea-level rise.

[13] "Silt" refers to sediment of all types carried in suspension.

TABLE I. RELATION OF BAY FILL TO "SILT" LOAD OF ENTERING RIVERS

| *Bay* | *Acre-Feet of Solid Fill per Century** | *River and Station†* | *"Silt" Load in Acre-Feet per Century* | *Ratio River Load and Bay Fill‡* |
|---|---|---|---|---|
| Corpus Christi | 31,590 | Nueces, Three Rivers | 49,400 | 1.56 |
| San Antonio | 23,070 | Guadalupe, Victoria,<br>San Antonio, Goliad | 77,500 | 3.36 |
| Lavaca | 4,155 | Lavaca, Edna | 10,800 | 2.61 |
| East Matagorda | 39,600 | Colorado, San Saba | 292,000 | 7.37 |
| Galveston | 86,400 | Trinity, Romayor,<br>San Jacinto, Huffman | 463,000 | 5.36 |

* Reduced to 30 per cent of volume because of the estimated water content.
† From Texas, 1952.
‡ The river "rafts" between 1865 and 1926 (Price and Gunter, 1942) probably led to the diversion of an unusually large amount of sediment to the flood plain, thus increasing this ratio.

In making such a comparison, however, it should be realized that some of the sediment is deposited on the flood plains or even behind dams[14] so that not all of the transported sediment will produce bay shoaling. Also some of the sediment is carried out of the bays and deposited in the open Gulf. On the other hand, there are other important sources of bay sediment in addition to the rivers, such as waste from cities, overwash from the barrier islands during hurricanes, wind blown sand from the barriers, erosion of bay bluffs and organic débris from the bay life. It is not unlikely that these are comparable in volume with the river load not deposited in the bays. Therefore, the excess of stream sediment available compared with bay shoaling could be interpreted as an indication of submergence for all except perhaps Corpus Christi Bay where the stream sediment nearly matches the bay shoaling.

## CONCLUSIONS

The examination and comparison of old soundings by the Coast and Geodetic Survey with recent soundings indicates that the Texas bays have shoaled an average of 0.82 foot in about 65 years which would mean 1.26 feet per century. Since the average bay depth is about 7 feet, this means that at the present rate, 1,000 years would see the elimination of most of the bays. It is notable, however, that borings and cores in the bays have yielded sediments which suggest that conditions similar to the present have been continuing for thousands of years and therefore, because of renewed sinking or sea-level rise, the bays may persist far longer than the present shoaling rate suggests. In this way thick sections of shallow bay sediment can develop.

In general the elimination of water volume in the bays by delta-building has been less significant than by deposition on the flat bay floors. It is only off the largest of the Texas rivers that delta-building has made an important contribution. It may be, however, that some parts of the coast where estuaries and lagoons are missing have been filled in by the rivers in the past. Thus the Brazos River, which transports more sediment than any other Texas river, has filled all embayments. Sand carried by wind from the dunes on the barrier islands and hurricane overwashes may be an important element in bay deposition but judged from the general absence of significant fill near the barrier islands these sources are not as significant as are the rivers.[15] Fill in small areas can be attributed to tidal deltas formed inside of small inlets. As indicated by the relative rise of sea-level at Galveston of 1.0 foot between 1901 and 1950 (Marmer, 1952), sedimentation may not be the only cause of depth changes. Subsidence is also suggested by the excess of river-carried "silt" over shoaling expectable from this source alone. Differential movement may be indicated by the deepening in West Galveston Bay and shoaling in East Bay. Deepening in bay entrances, on the other hand, is probably the result of the concentrated currents.

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[14] All of the large dams, however, were built toward the end of the interval between surveys.

The rate of bay sedimentation does not take account of the large pore space of the fine-grained sediments typical of the bays. The elimination of much of this pore space by subsequent compaction will drastically reduce the volume and will probably develop dips on the sides of the sandy barrier islands which may be favorable for future oil accumulations.

## REFERENCES

GUTENBERG, BENO, 1941, "Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior," *Bull. Geol. Soc. America*, Vol. 52, pp. 721–72.

MARMER, H. A., 1952, "Changes in Sea Level Determined from Tide Observations," *Proc. 2d Conf. on Coastal Engineering* (Houston, Texas, November, 1951), chapt. 6, pp. 62–67. Published by the Engineering Foundation, University of California.

PRICE, W. A., 1947, "Equilibrium of Form and Forces in Tidal Basins of Coast of Texas and Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 31, No. 9, pp. 1619–63.

———, AND GORDON GUNTER, 1942, "Certain Recent Geological and Biological Changes in South Texas, with Consideration of Probable Causes," *Proc. and Trans. Texas Acad. Sci.*, pp. 3–21.

TEXAS BOARD OF WATER ENGINEERS AND U. S. SOIL CONSERVATION SERVICE, DIV. OF IRRIGATION AND WATER CONSERVATION, 1952, "Progress Report No. 13 of Silt Load of Texas Streams (1950–1951)." 50 pp.

U. S. ENGINEERS, 1935, "Shore Protection of Galveston Bay, Harris County, Texas," *House Document 74*.

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[15] The significance of the sand, silt, and clay ratios in the sediment content in determining sources of sediment will be discussed elsewhere.

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# SHELLBACK Expedition

LTJG J. A. Knauss, USNR

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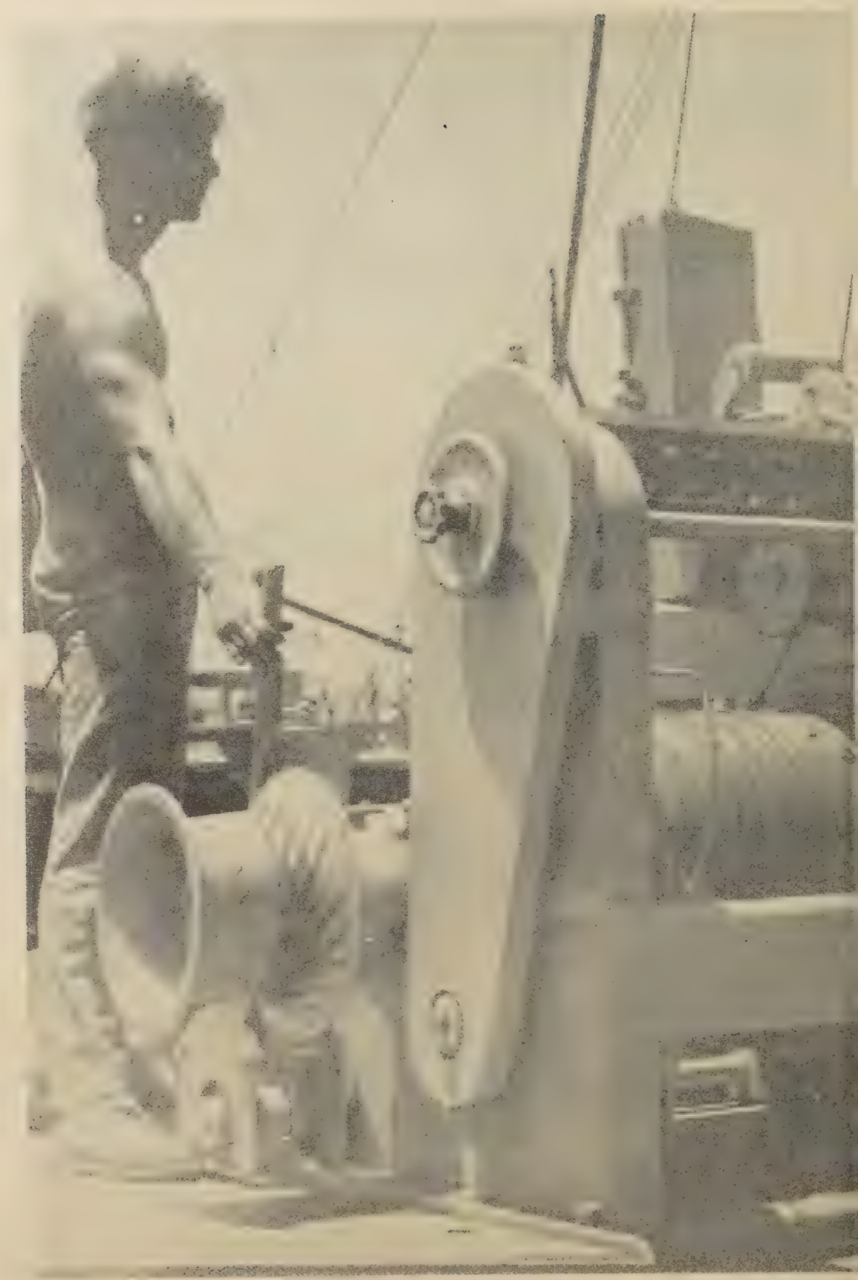


In the study of the oceans, man is largely dependent upon instrument that can be lowered to a predetermined depth to transmit information o bring back actual samples of the water or of the plants and creature that live in the water. Thus the winch, which lowers these instruments on the end of a steel cable to the desired depth, is an integral part of a oceanographic vessel.

# SHELLBACK Expedition

LTJG J. A. Knauss, USNR

...of the Geophysics Branch, ONR, participated in the SHELLBACK expedition as an oceanographer. He is working on his Ph. D. in this field at the University of California.

Since 1949 the Scripps Institution of Oceanography of the University of California has conducted, in cooperation with the Navy, a series of exploratory oceanographic cruises in the Pacific Ocean. Now, certainly the Pacific has been explored before. From the British CHALLENGER expedition (1873-76) to the Danish GALATHEA in 1951 and 1952 (Research Reviews, October 1952), various ships and scientists have studied the Pacific Ocean. But of necessity nearly all of these expeditions have had to sample sparsely. It has been the aim of the Scripps cruises, on the other hand, to study certain areas of the Pacific in some detail.

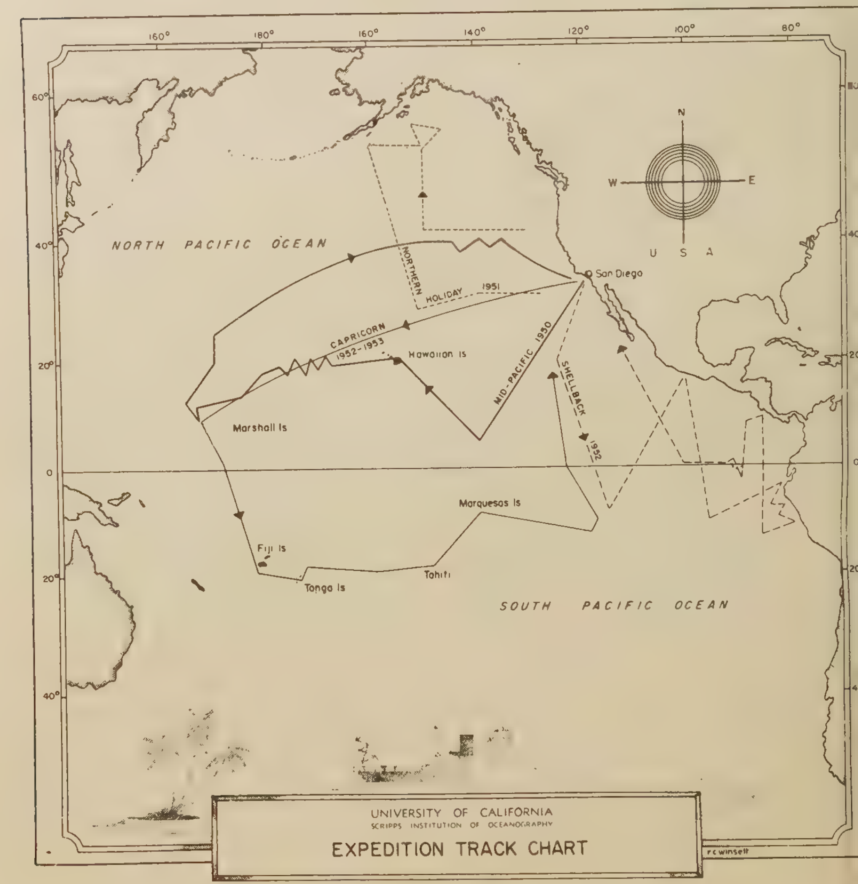
The tracks of the four Scripps cruises made to date are shown on the graph on p. 2. Essentially these expeditions have been of two different kinds. MIDPAC and CAPRICORN have been primarily geophysical and geological while NORTHERN HOLIDAY and SHELLBACK have been more concerned with what might be termed the classical studies in physical oceanography, that is, currents and water mass structure. However, regardless of the primary object, the ships are always crammed with as many additional scientists and their equipment for special projects as can be handled without disrupting the primary program.

The one Scripps vessel which has participated in all four of these expeditions is the research vessel HORIZON. The HORIZON is a 143-foot, 700-ton former ATA (auxiliary tug). The institution sails her with a crew of eighteen and has living accommodations for an equal number of scientists. This ratio (or a higher one) of scientists to crew is one which all private oceanographic vessels in this country try to maintain, since generally speaking the greater the ratio of scientists to crew, the less the "overhead" costs of an expedition.

The SHELLBACK cruise, in which the author participated, was not in any sense a single-institution operation. While the HORIZON was operating in the area shown on the chart, the U. S. Navy Electronics Laboratory's research vessel, the EPCE(R)857, was making measurements to the north, and the U. S. Fish and Wildlife Service, Pacific Oceanic Fisheries Investigation, which operates out of Hawaii, was making a series of stations to the west. Members of the oceanographic branch of NEL worked aboard the HORIZON, and several of the Scripps staff were aboard the EPCE(R). Also aboard the HORIZON were members of the Inter-American Tropical Tuna Commission and the U. S. Weather Bureau. In addition, one of the staff members from Scripps, with the assistance of the U. S. Air Force in Panama, made aerial reconnaissance studies over the operating area. The whole joint expedition was aptly dubbed Operation CO-OP.

The HORIZON left San Diego on May 17 and returned on August 27 1952. During this period it steamed some 14, 580 miles. Eight times i crossed the equator while sweeping back and forth across an area of fou million square miles. Its speed of advance, however, was slow becaus the ship stopped 216 times (every sixty miles) for about two hours t make an oceanographic station. These stations were the real heart o the SHELLBACK cruise, and it might be well to discuss in some detai what measurements were made and what is expected from then

The essential piece of equipment is a Nansen bottle and its rack o deep sea reversing thermometers. Some 10 to 15 such bottles are spacec along a wire and lowered in an open position down to a depth of abou 1500 meters. After the bottles have reached the desired depths, "messenger" (a small brass weight) is slid down the wire until it hits lever on the first bottle. It reverses the bottle and thermometer rac and closes the valve on the bottle; in this way a liter sample of wate from that depth is trapped inside. As the bottle is reversed it release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Marquesas Is
Fiji Is
Tonga Is
Tahiti
SOUTH PACIFIC OCEAN
UNIVERSITY OF CALIFORNIA
SCRIPPS INSTITUTION OF OCEANOGRAPHY
EXPEDITION TRACK CHART
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The HORIZON

a second messenger which in turn slides down the wire to trip the second bottle and release the third messenger; and so on until, barring misfires, all bottles have been tripped and water samples collected. At every other station, depth of water permitting, two such "casts" were made, a shallow cast at 1000 meters and a second at 1000 to 3000 meters.

By means of a delicate capillary system within the thermometer, turning the thermometers upside down cuts off the thread of mercury so that the thermometers can be brought to the surface still showing in situ temperatures. These thermometers are accurate to plus or minus .02 degrees centigrade.

For this accuracy to be attained, corrections must be made for the difference between the expansion coefficients of glass and mercury. However, because of this difference in expansion, it is possible to calculate the pressure and hence the depth from the difference in apparent temperatures of two thermometers attached to the same bottle—one in which the thermometer stem is protected from the outside water pressure and one in which it is not. This method of determining depth, which is good to about plus or minus five meters, is considered more accurate than simply measuring the amount of the wire out and correcting for the observed wire angle.

Water from the Nansen bottles was analyzed to determine its content of dissolved salt, oxygen, phosphate, and silicate ions. A network of closely spaced stations such as those made on SHELLBACK allows one to construct charts showing a three-dimensional distribution of salinity, temperature, oxygen, etc. It is then possible, using the temperature and salinity data, to construct charts showing density structure and, from this, to calculate the average current system and water transport. From analysis of the distribution of variables such as these, oceanographers gain insight into some of the large-scale dynamic processes of the ocean. Charts of this type are analogous in some respects to the preliminary mapping that geologists must do before they can begin to study possible causal relationships.

Supplementing the oceanographic stations, an even tighter network of temperature observations in the top layer of the ocean was provided by the bathythermograph, which was used about once every two hours as the ship traveled between stations. This instrument gives a continuous trace of temperature versus depth in the upper 900 feet, where the most rapid changes in temperature take place.

The method described of computing the ocean current structure from an analysis of the density gradients is not entirely satisfactory. The distance between stations, plus the several simplifying assumptions that have to be made in the calculations, mean that the current structure derived at best is only an average one, and that short period variations in time and in space are apt to be masked.

Therefore, another method was used on SHELLBACK to give a more instantaneous picture of the surface currents. Measurements as a function of the electrical voltage of the water were made every twenty miles. These voltage measurements can be related to the velocity of the surface waters but require assumptions as to the ratio of current width to depth. The truth of the matter is that no completely satisfactory method of measuring currents has been devised.

Along with the study of the water masses and ocean current characteristics, there is considerable interest in studying how life within the ocean is affected by changes in these factors. At each station two nets were lowered to sample the biological life. One, which was towed at a depth of 300 meters for twenty minutes, had a mouth one meter in diameter and a recording mechanism that measured the amount of water filtered during the tow. Observations of this type give a measure of variations in the total amount and in different types of plankton (floating-organisms). The other net used regularly was a small one with a 17-centimeter mouth, and with mesh openings of less than a tenth of a millimeter. This net, which was towed vertically through the upper 50 meters, collected even smaller organisms loosely classified by marine biologists as microplankton.

An additional 12 net hauls were made at a depth of about 4000 feet using a large net (with a mouth area of somewhat less than 100 square feet). Tows at this depth with large nets have been made but rarely in the past, and major interest in these hauls was in new or seldom collected species and in the occasional finding at these relatively great depths, of species thought to be indigenous to the surface waters.

On 37 stations water samples were drawn and treated with radioactive carbon. Some time later the sample was filtered and the amount of "carbon uptake" by the residual plankton was measured. These techniques are still in the experimental stage, but it is hoped that they will furnish a quantitative means of measuring plant productivity in the ocean.

Preparing to lower a sampling bottle to obtain data on temperature and salinity at great depths. (Photograph, courtesy of Scripps Institution of Oceanography)

Although, as stated earlier, the primary purpose of SHELLBACK was the study of currents and water masses, both geological and meteorological study programs went along simultaneously. The Weather Bureau personnel made regular surface and upper-air pilot balloon and radiosonde observations, which served two general purposes. They were coded and sent out over the Weather Bureau circuits to be added to the daily weather maps, but, of more lasting importance, they provide a series of upper air sections through the intertropical convergence in an area where few if any such sections exist.

Although no stops were made for coring or dredging the bottom, the ship's two echo sounders were kept running to give a continuous trace of the ocean floor. Occasionally when an unusual feature like a large seamount was passed over, the ship would turn and retrace its tracks, cutting the feature from several angles so that a general contour chart could be drawn. The amount of new information that marine geologists have gathered during and since the war about the morphology of the ocean basins is staggering and will be treated as a separate article at some future time in Research Reviews.

In oceanography, as in all sciences, the feeling of surprise about a new discovery is usually tempered by the long analysis and study that brings it forth. But there are dramatic exceptions. On SHELLBACK one quiet afternoon the echo sounder was etching a steady trace at 2300 fathoms when the pen began to rise, slowly at first, then more swiftly until, before it began to sink, it had traced the profile of a 12,000-foot mountain—a mountain that comes to within 268 fathoms of the surface, a mountain that no one had ever known about before, and which would still be unknown if the path of the HORIZON had been some twenty miles away in either direction.

The ship was gone from San Diego 103 days. During that time it stopped four times to take on fuel and provisions and to exchange passengers. Open house was held aboard the HORIZON at its stop in Lima, Peru. More than 200 guests came aboard at various times to inspect the vessel and its equipment. They represented the Navy, the fisheries and Guano industries, as well as the University of San Marcus and scientific societies. At Ecuador a delegation from the ship paid a visit to President Gallo Plaza, an alumnus of the University of California. Both in Peru and in Costa Rica informal discussions were held with government representatives concerning the Institution's oceanographic work and its relation to their fisheries resources program.

Planning for an oceanographic expedition of this kind, of course, begins many months before its departure, and analysis of the observations made goes on for several years after the ship returns home. As is almost inevitable in such a study, more questions were raised than answered. The results of SHELLBACK will be appearing as individual publications in scientific periodicals for the next few years. It is not fair at this time to anticipate the authors with any preliminary review of the results. As a matter of fact, those conclusions that appear obvious at the time they were made often turn out to be not very obvious after all. As somebody answered a question about results on the day the ship returned, "All I can tell you is how many tons of data I've collected."

644

MAO, HAN-LEE and KOZO YOSHIDA. Physical oceanography in the Marshall Islands area, 20°N-5°S, 155°E-175°E. SIO Reference 53-27, 30 pp., 1953. (Unavailable for exchange.)

ZOBELL, CLAUDE E. The occurence of bacteria in the deep sea and their significance for animal life. IUBS Deep Sea Colloquium, XIV Int. zool. Congr., Copenhagen, 1953. (To be published.)

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# Dimorphism in Larval Mouthparts in Spadefoot Toads of the *Scaphiopus hammondi* Group

GRACE L. ORTON

IN his recent discussion of the sporadic "beaked" variant in spadefoot tadpoles of the *Scaphiopus hammondi* group in western United States, Turner (1952) has concluded that differences in the contours of the larval beaks (= "mandibles") are not valid criteria for the separation of the three commonly recognized northern forms of the group, and that the structure of the beak does not change significantly between the approximately half-grown larval stage and metamorphosis.

Buccal dimorphism in larvae of western spadefoots has long been known and has been discussed briefly by several authors, of whom Turner appears to have been the first to treat the character on the basis of population samples from widely separated localities. The problem s somewhat more complicated than he has ndicated, however, and it warrants much further study. Ideally, it should be worked out along with a thorough basic review of the systematics of the genus. The *hammondi* group s not yet adequately understood, and the broad overlap in the ranges of *S. h. hammondi* and *S. h. bombifrons*, as currently defined, is perhaps an important factor in the larval problem. The present paper reviews the background of the problem and discusses some of the lines of investigation that may help to provide a satisfactory solution.

Gilmore (1924) described dimorphic spadeoot larvae, referred to *S. hammondi bombifrons*, rom the vicinity of Colorado Springs, Coloado. The larvae with hypertrophied mouthparts had markedly carnivorous habits. The beaks of these individuals were enlarged and hickened, the upper bearing a strong median cusp and the lower a pair of such structures eparated by a deep notch. The jaw muscles were greatly enlarged, conspicuously modifying he contours of the head. This locality is near he Colorado limit of *bombifrons*, which is predominantly a Great Plains form, and is near the zone in which the ranges of *bombifrons* nd *hammondi* are currently understood to meet or overlap (Turner, 1952, fig. 2; Wright nd Wright, 1949, map 6; Stebbins, 1951, pl. 55). Smith (1934) quoted extensively from Gilmore, and described and figured the strongly cusped mouthparts of a carnivorous type of tadpole collected near Grant, Valencia County, New Mexico. No mention was made of the jaw musculature, but it was noted that the larvae had "small partially devoured tadpoles in their mouths," when collected. Smith contrasted these carnivorous larvae with specimens referred to typical *hammondi* by Storer (1925) and by Wright (1929), and concluded that the "differences are so marked that there can be little doubt of their specific value."

Tanner (1939) described tadpoles which he referred to the newly revived *intermontanus*. In these larvae the upper beak had serrated edges and a "median point," and the lower beak had a median notch which, however, lacked projections at its sides. He indicated that these specimens agreed more closely with *hammondi*, as described by Storer (1925), than with *bombifrons*, as described by Smith (1934).

From the vicinity of Las Vegas, New Mexico, within the region where the ranges of *hammondi* and *bombifrons* are now understood to overlap widely, Bragg (1941a, b) reported adults of both forms and larvae of two kinds, conforming respectively to the heavy-jawed type referred to *bombifrons* by Gilmore and Smith and to the thin-beaked type referred to *hammondi* by Storer and Wright. "During the breeding congresses," Bragg (1941a: 93) stated, "some pools contained only *S. hammondii*, some only *S. bombifrons*, and still others a mixture of the two species. In every case, the tadpoles later found conformed to expectations." Previously, he had found that in central Oklahoma adult spadefoots have the characters of *bombifrons*, whereas the larvae are uniformly of the thin-beaked type described by Storer and Wright for *hammondi*. Bragg apparently assumed that the larval differences are constant and wholly characteristic of the respective forms of *Scaphiopus*, as one would expect them to be. On the basis of his observations in both Oklahoma and New Mexico, he concluded that the original identifications of larvae in this group of spadefoots had been confused and should be reversed: that the heavy-jawed form with prominent cusps on the beaks should be called *hammondi* and the thin-beaked form *bombifrons*. This change in larval identifications was accepted by Wright and Wright (1949) and by Smith (1950), and was tentatively followed by Stebbins (1951), who, however, cited exceptions in beak structure in larval samples of all three forms under consideration.

From variational data on nine scattered populations, Turner (*op. cit.*) concluded that the forms in the *hammondi* group are not separable on the basis of the mouthparts, for *hammondi* and *bombifrons* each may have a distinct median projection on the upper beak as a relatively uncommon modification, and the lower beak may be notched in all three forms. "Indeed, in certain samples, the variation within one population may be of the same magnitude as that which has been formerly supposed to differentiate subspecies. . . . That it [median cusp on upper beak] might be regularly present in a certain population or even within all populations in some areas is possible, however, and this may be the basis for the statements that it is a diagnostic character in *Scaphiopus h. hammondi*." Turner recognized, as Bragg apparently had not, that modified beak contours may characterize individuals rather than populations. Unfortunately, however, the specialized larvae on which Turner's observations and illustrations are based are actually only intermediates. He apparently did not have examples of the extreme variant with excessively hypertrophied beaks and jaw muscles on which Gilmore (1924) and Smith (1934) based their observations. The degree of enlargement of mouthparts is subject to wide variation in these larvae. So far as I know, the most extreme condition is that reported by Gilmore. I have examined some of his specimens in the collection of the University of Michigan Museum of Zoology (UMMZ).

Spadefoot larvae with greatly hypertrophied mouthparts have been reported from Colorado Springs, El Paso County, Colorado (Gilmore, 1924); Grant, Valencia County, New Mexico (Smith, 1934); and Las Vegas, San Miguel County, New Mexico (Bragg, 1941a, b). All of these localities are in or near the region
overlap in the ranges of *hammondi* and *bom*
*frons*, and the identification of individual lar
is thus somewhat open to question. I do
know of any published records of the extre
variant in additional localities, but one sp
men of this type is included in a series of
spadefoot tadpoles from near Kadoka, Jack
County, South Dakota (UMMZ 76558–
This locality is at or near the eastern limit
the range of *bombifrons* in the state, as mapp
and is far distant from the nearest known loc
ties of *hammondi* and *intermontanus*. It t
constitutes a definite record of occurrence
the extreme variant in *bombifrons*.

Studies on larval dimorphism in the *h*
*mondi* group should be extended to incl
Mexican populations of *hammondi* and *bom*
*frons*, and the southern representative of
group, *multiplicatus*, which occurs over
central and southern parts of the Mexi
plateau, southward to Oaxaca. Taylor (19
reported that tadpoles which he regarded
topotypic of *multiplicatus* (from El Guar
southwest of Mexico City) showed no trac
cusps on the beaks. The University of Michi
collection contains two series of spade
tadpoles from different localities in San
Potosí, México. These larvae are of mode
size, about 20–45 mm. in total length. A se
of 80 tadpoles includes one individual
exceptionally large jaw muscles, which re
the larval arrangement although the speci
is in an early stage of transformation and
already shed the beaks. In the second se
5 of the 76 tadpoles have the jaw mu
somewhat enlarged and have a modera
developed median cusp on the upper beak
median notch on the lower beak. They
relatively wider lips, more sharply ser
beaks, and a flatter snout profile tha
unmodified larvae in the same series.
specialized individuals are roughly interme
in extent of modification. These two seri
tadpoles are probably referable to ty
*multiplicatus*, but whatever their eve
identification they are from localities geog
ically remote from the regions in which
hypertrophy has been reported previously
they further demonstrate that this modific
of the mouthparts is of very widespread o
rence.

Larvae with extremely modified beaks and larged jaw muscles and cartilages have, thus, en taken in several parts of the range of *mbifrons*, including the area in the southwest iere the range of this form is now considered overlap broadly that of *hammondi*, and in at ıst some populations both specialized and rmal individuals occur together. Variously termediate larvae, such as those described d figured by Turner, are known from widely parated populations in all three northern rms and in *multiplicatus*. The available evince suggests the possibility that in the *hamndi* group in general there is an unstable end toward overdevelopment of the mouthrts as a variant character, and that this end may reach its extreme expression in *mbifrons*. The geographic and systematic nits of this variant, in all gradations of its pression, need to be determined more presely. Breeding experiments could establish iether the jaw modifications have a definite netic basis. Half-grown larvae can easily be entified to type, but so far as I know no one s traced the development of both types from tching onward, to determine with certainty iether the differences appear during the forıtion of the mouthparts or whether there is vergence of structure after the feeding patrn of the individual has become established. is theoretically possible that overdevelopent of the jaw region might follow secondarily excessive exercise") from a basic difference individual feeding preferences, but it is also ssible that the feeding pattern itself may be netically determined. Ecological factors af-ting the larvae should be studied more fully. ie selective advantage of the polymorphic pes, and consequently their numerical ratios, ght differ from year to year in the same popıtion. The unusual variability in mouthparts y itself be an important adaptive character, dening the limits within which a successful ır-class might be obtained.

It would be instructive to make detailed nparative studies of larval food preferences l modes of feeding in the *hammondi* and *brooki* groups. "Cannibalism" has been orted in eastern *holbrooki*, but aggressive dation in contrast to simple scavenging on tein material is apparently not a normal ding pattern in this form (Richmond, 1947), and so far as I know no evidence of buccal dimorphism has been found.

The tadpoles of relatively few species are known to have excessive enlargement and heavy muscular development of the mouthparts and associated carnivorous or aggressively predatory food habits. The examples are, however, well scattered taxonomically and geographically and are known from a variety of ecological situations. They include *Hoplophryne rogersi* (Microhylidae, Africa); *Ceratophrys dorsata* and *C. ornata* (Leptodactylidae, South America); the four Jamaican forms of *Hyla* (Hylidae); and the *Rana rugulosa* group (Ranidae, tropical Africa and southeastern Asia). In these forms enlarged and strengthened jaw apparatus appears to be a normal larval characteristic of the species rather than a sporadic variant. This is a striking difference from the condition in the *Scaphiopus hammondi* group, and leads one to speculate whether the variant larval type in the *hammondi* group may be undergoing an early phase of evolution, already widely distributed but perhaps still having a very low gene frequency in most populations. If the maximum expression of this variation should prove to be genetically characteristic of *bombifrons*, one could consider the possibility that in the broad area of overlap of the ranges of *bombifrons* and *hammondi* this character may, through introgression, be entering into stocks that are genetically *hammondi*.

The buccal dimorphism in the *Scaphiopus hammondi* group is an excellent example of the larval problems that are abundant in the amphibians and that require, for solution, application of the wide range of methods and resources now available to the systematist.

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## LITERATURE CITED

BRAGG, ARTHUR N. 1941a. Tadpoles of *Scaphiopus bombifrons* and *Scaphiopus hammondii*. *Wasmann Coll., 4 (3): 92–4.*

——— 1941b. Some observations on amphibia at and near Las Vegas, New Mexico. *Great Basin Nat., 2 (3): 109–17.*

GILMORE, R. J. 1924. Notes on the life history and feeding habits of the spadefoot toad of the western plains. *Colorado Coll. Publ., Sci. Ser., 13 (1): 1–12.*

RICHMOND, NEIL D. 1947. Life history of *Scaphiopus holbrookii holbrookii* (Harlan). Part

I: Larval development and behavior. *Ecol., 28 (1): 53–67.*

Smith, Hobart M. 1934. The amphibians of Kansas. *Amer. Midl. Nat., 15 (4): 377–528.*

——— 1950. Handbook of amphibians and reptiles of Kansas. *Univ. Kansas Mus. Zool., Misc. Publ., (2): 1–336.*

Stebbins, Robert C. 1951. Amphibians of western North America. *Univ. California Press: ix + 539.*

Storer, Tracy I. 1925. A synopsis of the amphibia of California. *Univ. California Publ. Zool., 27: 1–342.*

Tanner, Vasco M. 1939. A study of the genus *Scaphiopus. Great Basin Nat., 1: 3–20.*

Taylor, Edward H. 1942. Tadpoles of Mexi
anura. *Univ. Kansas Sci. Bull., 28 (3): 37–55.*

Turner, Frederick B. 1952. The mouth pa
of tadpoles of the spadefoot toad, *Scaphio
hammondi.* Copeia *(3): 172–5.*

Wright, Albert H. 1929. Synopsis and
scription of North American tadpoles. *Proc.
S. Nat. Mus., 74 (11): 1–70.*

———, and Anna A. Wright. 1949. Handbo
of frogs and toads of the United States and C
ada. *3rd ed. Comstock Publ. Co.: xii + 640.*

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fornia.

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# EISTOCENE AND RECENT SEDIMENT FROM THE FLOOR OF THE NORTHEASTERN PACIFIC OCEAN

BY HENRY W. MENARD

## ABSTRACT

ven dredge hauls on seamounts, and nine cores of the sea floor show that glacial marine drift was de- ed over several hundred thousand square miles of the northeastern Pacific during Pleistocene time. ice-rafted pebbles are covered by as much as 50 mm of manganese dioxide, suggesting a minimum age ,000 years.

ice glacial marine sedimentation ceased, blue mud has spread out from shore. The drift is covered by st 127 cm of blue mud at a distance of 250 miles from shore. Southeast of Kodiak, Alaska, blue mud is ed by a thin layer of ash from the 1912 eruption of Katmai Volcano.

-rafted pebbles surrounded by envelopes of well-sorted coarse sand are incased in pieces of a thick anese crust from Gilbert Seamount. The pebbles settled on the relatively smooth surface of the man- e crust and were incased by the slow upward growth of the crust. Finer sediment, which settled from rgs, was swept off the smooth crust except for well-sorted coarse sand which collected in the pockets e crust surrounding the larger pebbles. The formation of the pockets and the envelopes of coarse sand ribed to the action of weak currents although the specimens were dredged from a depth of at least feet.

## CONTENTS

### TEXT

Page
duction .......... 1279
pedition "Northern Holiday" .......... 1279
evious investigations .......... 1280
knowledgments .......... 1281
ods .......... 1281
uipment and sampling techniques .......... 1281
boratory techniques .......... 1281
nary of results .......... 1282
n and age of the marine gravel .......... 1282
acial-marine origin .......... 1282
e of the glacial drift .......... 1282
ocene and Recent sediment distributions 1283
tent of Pleistocene ice .......... 1283
anges in sediment distribution .......... 1287
n from Katmai Volcano .......... 1288
ence of deep currents .......... 1290
ur on Gilbert Seamount .......... 1290
d layers in core 2 .......... 1292
lusion .......... 1292
ences cited .......... 1292

### ILLUSTRATIONS

Figure Page
1. Distribution of marine sediment in Pleistocene time .......... 1280
2. Present distribution of marine sediment .......... 1287
3. Distribution of sand and gravel in deep-sea cores .......... 1289
4. Pocket in a crust of manganese, and the pebble found in the pocket .......... 1290
5. Supposed origin of pockets in a manganese crust on a seamount .......... 1291

Plate Facing page
1. Chain-bag dredge and kelp-rafted sediment .......... 1282
2. Dredge hauls .......... 1283

### TABLES

Table Page
1. Description of dredge hauls .......... 1284
2. Description of cores .......... 1285

## INTRODUCTION

### *Expedition "Northern Holiday"*

pedition "Northern Holiday" was carried in July, August, and September of 1951 e Scripps Institution of Oceanography with the co-operation of the U. S. Navy Electronics Laboratory. The scientific program included physical and chemical oceanography and marine biology as well as marine geology, so only a part of expedition time was available for dredging and coring. The general results of the whole

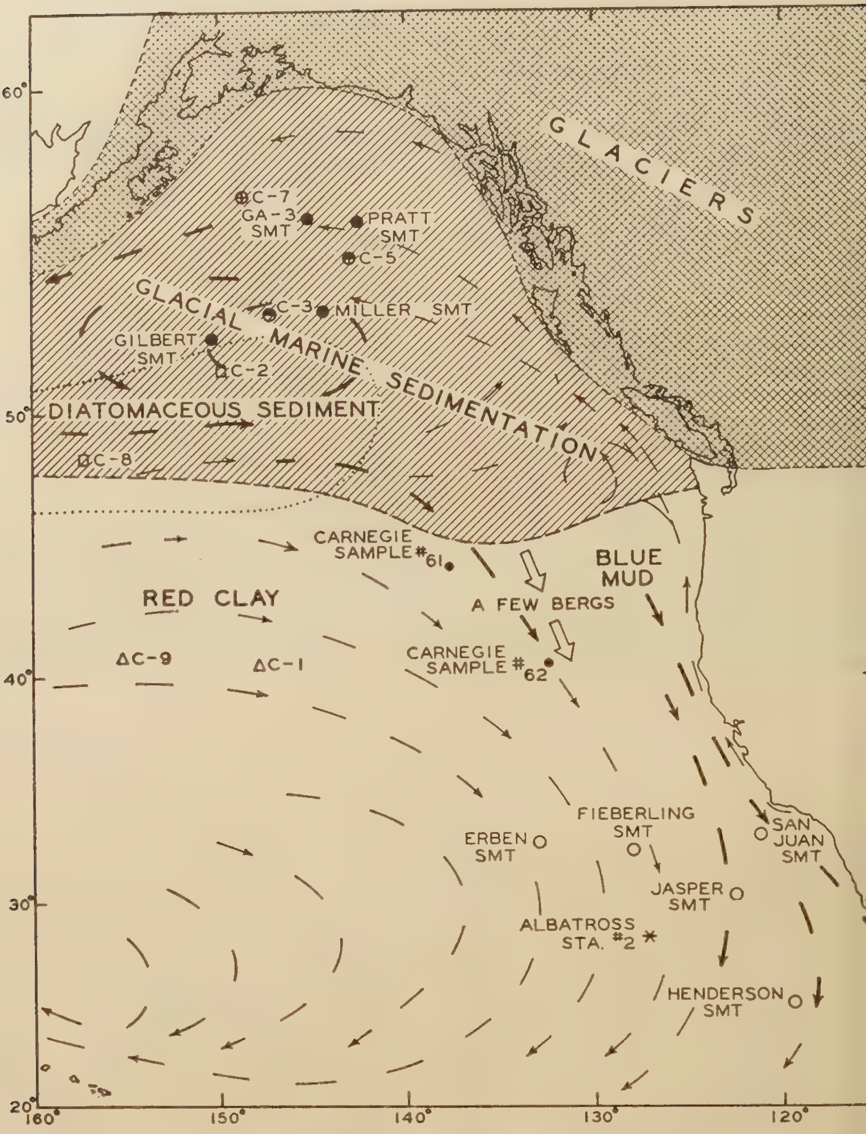
60°
50°
40°
30°
20°
160°
150°
140°
130°
120°
GLACIERS
C-7
GA-3 SMT
PRATT SMT
C-5
GLACIAL MARINE SEDIMENTATION
C-3
MILLER SMT
GILBERT SMT
C-2
DIATOMACEOUS SEDIMENT
C-8
CARNEGIE SAMPLE #61
BLUE MUD
RED CLAY
A FEW BERGS
C-9
C-1
CARNEGIE SAMPLE #62
FIEBERLING SMT
ERBEN SMT
SAN JUAN SMT
JASPER SMT
ALBATROSS STA. #2
HENDERSON SMT

FIGURE 1.—DISTRIBUTION OF MARINE SEDIMENT IN PLEISTOCENE TIME

expedition and plans for future work on the samples and observations are summarized by Wooster (1951). During the expedition, four seamounts were dredged in the Gulf of Alaska, and the deep-sea floor was cored in nine places in the northeastern Pacific Ocean (Fig. 1). Many of the samples contain glacial marine sediments of the types widely distributed in the Atlantic Ocean (Peach, 1912; Bramlette and Bradley, 1940), the southern Indian Ocean (Murray and Philippi, 1908), and the A

Ocean (Hough, 1950).

### *Previous Investigations*

Pleistocene glaciers fringed the

Alaska, so ice-rafted sediment was ex

in the Gulf, although none had previous

reported. The U.S.S. TUSCARORA (E

1874) and the U.S.S. ALBATROSS (Mu

ssiz *et al.*, 1902) took surface samples in the
f of Alaska, and similar samples have been
ected by U. S. Coast and Geodetic Survey
s (Tyler, 1931). Neither these samples nor
ers collected in the more southerly parts of
northeastern Pacific contain sediment previ-
y attributed to ice rafting, except for one
ut 600 miles west-southwest of San Diego,
ifornia (Agassiz *et al.*, 1902, p. 71). This
aordinary sample will be discussed in con-
tion with the distribution of Pleistocene
ting ice in the northeastern Pacific Ocean.
he "Northern Holiday" marine geology
gram in the Gulf of Alaska was designed
est the hypotheses of Menard and Dietz
51, p. 1277–1285) as to the age and history
he seamounts. It was hoped that dredging
coring on seamounts would recover fossilif-
s bedrock, but none of the bedrock dredged
n side slopes was fossiliferous; however, the
rts of the party were amply compensated
the recovery of the dredge hauls of glacial
ine drift, which are the main subject of the
ent paper.

### *Acknowledgments*

he samples were collected on board the
pps Institution of Oceanography research
el HORIZON, James L. Faughn, Master.
chief scientists were John D. Isaacs up to
liak, Alaska, and Warren S. Wooster on the
rn to San Diego. All members of the scien-
party and many of the crew co-operated in
ng, dredging, and surveying; the writer is
icularly indebted to Harris B. Stewart who
a large share of the responsibility for dredg-
and surveying with tireless enthusiasm
good humor. The sea-floor cores were
ected primarily for a study of Radiolaria
V. R. Reidel, who has made them available
he writer.

lentifications of heavy minerals and For-
ifera were made by E. L. Hamilton to
m the writer is indebted also for critical
ssion of the manuscript in all stages of its
lopment. Many of the writer's other col-
ues of the Scripps Institution of Oceanog-
y and the Navy Electronics Laboratory
contributed to this investigation. The
ments and suggestions of M. N. Bramlette
R. S. Dietz have been particularly helpful.

## METHODS

### *Equipment and Sampling Techniques*

Dredge hauls on seamounts were made with a chain-bag dredge constructed at the Navy Electronics Laboratory for heavy-duty operations in the deep sea (Pl. 1, fig. 1). Steel plate half an inch thick and 10 inches wide frames the dredge mouth which measures 14 inches by 36 inches and resembles a box open at both ends. Behind the mouth is a bag made of 5-foot lengths of 1-inch chain wired together side by side and at the bottom. Another, longer bag of fish net with a half-inch mesh lies inside the chain bag and serves to retain finer material.

Pipe dredges were attached to the end of the chain bag by short lengths of chain. These simple dredges are short lenghs of 2½-inch pipe with attached cloth bags that retain sand.

The dredges were towed upslope at speeds of ½ to 2 knots with about 10 to 20 per cent more wire out than the depth indicated on the echo sounder. When the dredge was dragging over bedrock, the amount of pull indicated on a dynamometer was used to show if it was on bottom. Minor jerks and twitches of the wire could be felt even when dredging unconsolidated marine drift. The absence of such movement was taken as an indication that the dredge was above the bottom.

The corer used was similar to one developed by Fred B Phleger (Phleger and Parker, 1951, Pl. 2, fig. 1) but modified by the addition of heavier weights and a longer core barrel. This instrument obtains cores 1⅜ inches in diameter and up to 6 feet long. The cores were retained in the plastic tubes, which line the corer, and were not opened on board ship; however, a rough field description was made of the top and bottom of the cores before the tubes were corked. The depth of penetration, as indicated by sediment sticking to the outside of the coring tube, was determined in order to measure the shortening of the sample (Piggot, 1941; Emery and Dietz, 1941).

### *Laboratory Techniques*

The plastic core liners and the samples were cut in half lengthwise. The tops and bottoms of the cores were sampled twice; one set of samples was retained by W. Reidel, and the other set by E. L. Hamilton and the writer. The writer examined the cores with a binocular microscope and described any changes in color and grain size. Small samples were taken 5 or 10 cm apart or in every distinct layer. These samples were agitated and repeatedly decanted. The percentage of sand material in the original sample was estimated on the basis of the volume of the residue, and all grains of diameter of 1 mm or larger were counted and measured. Where this technique showed the presence of Foraminifera, a second sample was taken to be sieved because some tests were lost by the decantation. The samples from the tops, bottoms, and significant points in the cores were washed on 173-mesh bolting silk, and the percentages of Foraminifera and diatoms were roughly estimated by Hamilton and the writer. Hamilton subsequently identified these Foraminifera and also the minerals in the well-sorted sand layers in Core 2. Reidel examined the other set of samples for Radiolaria and diatoms. He has been kind enough to give the writer estimates of the percentage of diatoms based on a microscopic inspection of unwashed samples.

## Summary of Results

The positions, depths, instruments, notes on collecting, and descriptions of the samples are summarized in Tables 1 and 2. Dredge hauls from Gilbert and Miller seamounts are shown in Plate 2. Schematic longitudinal cross sections of the cores appear in Figure 3.

## Origin and Age of the Marine Gravel

### *Glacial-Marine Origin*

The varied lithology, large particle size, poor sorting, and wide range of rounding of the sediment from the seamounts and from some cores leave little doubt that it was rafted into place. Floating ice is not now found in the Gulf of Alaska (Hydrographic Office, 1946, p. 3–18); but Pleistocene glaciers reached the continental
shelf in the area (Flint, 1947, p. 223)
floating ice must have been widespread
open sea. This ice appears to be the only
capable of transporting so much coarse
ment so far. The sediment may be called
*drift* or simply *drift* according to both the
inal and present meanings of the terms (
1947, p. 102). Some fraction of the sed
may have been rafted by kelp (Emer
Tschudy, 1941). A floating clump of *Nere*
(Pl. 1, fig. 2) about 30 feet long was col
just east of Gilbert Seamount and roughl
miles from the nearest shallow water wh
could have grown. The holdfast of one
inclosed a fine-grained calcareous sanc
cobble measuring 80 x 50 x 40 mm. S
pieces of kelp were grappled from the
of the open Gulf in other places, and many
sighted each day. If 1951 was a represen
year, considerable material has been trans
into the Gulf of Alaska by kelp since th
ice age.

### *Age of the Glacial Drift*

No ice is found in the open waters of th
of Alaska, so the glacial drift dredged fro
mounts must have been deposited by a
ice. The manganese film on the coarse
confirms its antiquity because the rate o
ganese deposition is very slow. Pett
(1943) measured the rate of growth of m
nese nodules by radioactivity analysis and
it to be about 1 mm/1000 years. If this
even of the right order of magnitude, m
nese must not have been deposited in th
of Alaska during most of postglacial ti
cause the coating is much less than 1 mm
Evidence from other parts of the Pacifi
cates that manganese deposition is intern
or else that the long-term rate is two o
orders of magnitude slower than Pette
determination. For example, some of th
mounts of the Mid-Pacific Mountains hav
under water since Cretaceous time (Ha
1951), and Erben Seamount has been sub
since middle Tertiary time (Carsola and

Plate 1. CHAIN-BAG DREDGE AND KELP-RAFTED SEDIMENT

Figure 1. Chain-Bag Dredge

Figure 2. Kelp-Rafted Sediment

Clump of *Nereocystis* with a cobble in one holdfast.

52, p. 493), yet none appear to have a cover more than 100 mm of manganese dioxide. In addition to glacial drift, the dredge haul Gilbert Seamount (NH D-1) included several gments of manganese dioxide crust with a ickness of about 5 cm and an area as large as cm square. The fragments are rather flat; e top is smooth except for shallow creases and v folds like those found on thick hide; the ttom grades into yellowish-white, weathered, rthy material rich in phillipsite and other eration products. It appears that the fragents are parts of an extensive manganese ust formed on the weathered volcanic bedck of the seamount. Scattered pebbles of sandne, shale, basalt, and quartz, inclosed in velopes of well-sorted coarse sand (Figs. 4, , are randomly distributed at all depths thin the crust. The pebbles were rafted over e seamount from the time that the crust first gan to form more than 50,000 years ago asming the rate of deposition determined by ttersson. However, thin laminations within e crust show that deposition was intermittent, the total time involved may have been more an 50,000 years. Judging by the thickness of nganese crust on other seamounts which have known minimum age, the crust on Gilbert amount may represent more than the whole the Pleistocene. The observed relations been the erratic pebbles and the deposition of nganese on Gilbert Seamount permit only o conclusions:

(1) The unconsolidated drift is coated with ery thin layer of manganese dioxide and is atively recent. (Presumably it was deposited her in the last glacial substage of the Wiscon- or during the whole of Wisconsin time.)

2) The erratic pebbles incased in the mangae crust are much older than the unconsoliied drift. (They may have been deposited by ting ice during Wisconsin substages, or dur- the whole Pleistocene Epoch; or, conceivy, some may have been deposited by floating or other means at any time.)

## Pleistocene and Recent Sediment Distributions

### *Extent of Pleistocene Ice*

Pebbles and coarse sand in Cores 2, 3, 4, and 8 indicate glacial marine sedimentation. In contrast, the red clay in Cores 1 and 9 contains no sand except authigenic manganese dioxide flakes. These cores, respectively 132 cm and 180 cm long, represent roughly 132,000 years and 180,000 years of deposition according to the rates of deposition given by Kuenen (1950, p. 384) so they would have penetrated at least to Wisconsin marine till if it were present. Apparently the southern limit of effective ice transport lay between the locations of the two types of cores (Fig. 1). Nearer the shore of the United States, the southern limit of Pleistocene floating ice is very poorly defined because the normal spread of terrigenous material from the continent obscures ice-rafted sediment. However, Revelle (1944, p. 32–33) finds that Carnegie Sample No. 61 (about 650 miles from shore, Fig. 1) is a gray clayey mud and believes "The color of this sample indicates terrigenous influence even though the distance from shore is great and the nitrogen content is not larger than that of other north Pacific clays." The terrigenous influence may be doubtfully referred to glacial marine transportation. To the southeast, Carnegie Sample No. 62 is a normal red clay (Revelle, 1944, p. 32) although it is roughly 250 miles closer to shore than No. 61 (Fig. 1).

One of the most unusual samples ever collected from the northeastern Pacific was dredged by the U. S. Fish Commission ship Albatross at Station No. 2 of Alexander Agassiz' third expedition in 1899–1900 (Fig. 1). According to Agassiz (1902, p. 71), the dredge contained red clay and manganese nodules as well as a few rocks thinly coated with manganese. The rocks were pebbles of:

hornblende andesite, rounded
pale-green serpentine, subangular

---

Plate 2.—DREDGE HAULS

Figure 1. Marine Drift from Gilbert Seamount

Figure 2. Volcanic Bedrock and Marine Drift

rom the side slope of Miller Seamount.

TABLE 1.—DESCRIPTION OF DREDGE HAULS

| Sample | Lat. and Long. | Topographic position | Depth in fathoms | Instrument and sampling notes | Description of sample |
|---|---|---|---|---|---|
| NH D-1 | 52–47 N.<br>150–05 W. | Gilbert Smt., near top | 800–850 | chain bag dredge and two pipe dredges, pipe dredges lost | About 500 pebbles, cobbles, boulders, largest 20 x 30 x 33 Most angular, some rounded. V ous types of igneous, metamor and sedimentary rocks. Se pieces of $MnO_2$ crust as larg 15 cm square and 5 cm thick large rocks and many small coated with a film of $MnO_2$. S stone, shale, basalt, and q pebbles imbedded in the M crust. |
| NH D-2 | 53–32 N.<br>144–17 W. | Miller Smt., just below break in slope | 550–600 | chain bag dredge and two pipe dredges, pipe dredge bags torn and empty | One cetacean ear bone, one of $MnO_2$ crust 5 x 20 cm, 1 thick. |
| NH D-3 | 53–32 N.<br>144–17 W. | Miller Smt., on side slope | 600–850 | chain bag dredge and two pipe dredges, pipe dredge bags torn and empty, dynamometer pull reached 3½ tons | About 40 pounds of rocks, la vesicular basalt with fresh fract unfractured surfaces coated wi much as 2 mm $MnO_2$. Some s pieces of $MnO_2$ crust 1 cm t Seven angular to rounded ign and metamorphic rocks coated a $MnO_2$ film, largest 10 x 20 x 2 |
| NH D-4 | 56–20 N.<br>142–30 W. | Pratt Smt., on flat top | 400 | chain bag dredge and one pipe dredge | About 60 pounds of gravel sand, angular to well-rounded neous, metamorphic, and sedi tary rocks, largest 10 x 12 x 2 Most rocks coated with a fil $MnO_2$. Abundant forams in sa |
| NH D-5 | 56–20 N.<br>142–30 W. | Pratt Smt., near break in slope | 500 | chain bag dredge and two pipe dredges | About 100 angular to well-rou igneous, metamorphic, and mentary rocks coated with a M film, largest 5 x 5 x 20 cm. One $MnO_2$ chip 4 mm thick. dredges held 1 gallon of poorly sorted sand and gravel abundant forams. |
| NH D-6 | 56–10 N.<br>145–15 W. | Seamount GA-3*, near break in slope | 500 | chain bag dredge and two pipe dredges, chain bag empty | Poorly sorted sand and g angular to rounded pebbles neous and sedimentary r largest 5 cm diameter. forams in sand. |
| NH D-7 | 56–10 N.<br>145–15 W. | Seamount GA-3*, side slope | 750–1000 | chain bag dredge and two pipe dredges, dynamometer pull reached 3 tons | Freshly fractured volcanic br unfractured surfaces coated $MnO_2$ crust as much as 5 cm A few rounded basalt pebble bedded in the $MnO_2$ crust. |

* According to the numbering of Menard and Dietz (1951).

TABLE 2.—DESCRIPTION OF CORES

C-1 (40° 31.44′ N., 147° 58.5′ W., 2550 fathoms, 114 cm long, depth of penetration 132 cm)

ed clay throughout. No material of sand size except $MnO_2$ flakes.

C-2 (51° 34.5′ N., 149° 57.7′ W., 2450 fathoms, 145 cm long, depth of penetration 157 cm)

| | |
|---|---|
| 0–6 cm | Muddy diatom ooze, yellowish brown grading downward to dark yellow brown. Some sand, largest grains 1 mm. No forams. |
| 6–37 cm | Light olive-gray clay. Some sand. |
| 7–39 cm | Increasingly sandy. |
| 9–40 cm | Well-sorted fine sand layer. Hamilton identifies the following minerals: quartz, orthoclase, albite (rare), calcite, glass, hypersthene, biotite, hornblende, augite, garnet, magnetite, apatite, zircon, and iron oxides. |
| 0–56 cm | Diatom ooze, light olive gray grading to dusky yellow. A few coarse sand grains. |
| 6–60 cm | Dusky yellow clay with fine sand. |
| 0–70 cm | Dusky yellow-brown mud. Some sand, largest 5 mm. Diatoms abundant. |
| 0–84 cm | Light olive-gray mud. |
| 4–85 cm | Fine sand layer very rich in diatoms. Under a binocular microscope the sand is seen to be divided into three well-sorted sand layers each of different size. Graded bedding is not evident. Contains the same mineral suite as the sand layer at 39–40 cm except that albite is absent. |
| 5–103 cm | Light olive-gray ooze with some sand grains. |
| 3–105 cm | Transition to brown clay. Some sand grains. |
| 5–112 cm | Dusky yellow-brown clay, darker at base. Some sand grains. |
| 2–124 cm | Light olive-gray mud with some sand. |
| 4–126 cm | Well-sorted fine sand. Contains the same mineral suite as the sand layer at 39–40 cm except that albite is absent, and oligoclase and clinozoisite are present. |
| 6–145 cm | Light olive-gray ooze grading to more brownish downward. Some sand. |
| 5 cm<br>ottom) | Well-sorted fine sand, very rich in diatoms. Largest grain 5 mm in diameter. No forams. |

C-3 (53° 22.6′ N., 147° 13.6′ W., 2300 fathoms, 36 cm long, depth of penetration 63 cm)

| | |
|---|---|
| op | Diatomaceous sandy mud. About one third sand includes mineral grains and rock chips, largest 8 mm across. No forams. |
| cm | A 20-mm pebble in sand. |
| cm | (bottom) Sandy mud, largest grains 2 mm diameter. Diatoms rare, no forams. |

C-4 (Top of Miller Seamount, 560 fathoms)

few very small pebbles of granite, sandstone and quartz, and $MnO_2$ chips in core catcher.

C-5 (55° 07.8′ N., 142° 55′ W., 2030 fathoms, 127 cm long, depth of penetration 127 cm)

| | |
|---|---|
| 21 cm<br>op) | Reddish-brown mud, apparently the oxidized top zone of a blue mud. |

| | |
|---|---|
| Top | Very diatomaceous mud. No forams. No grains larger than 0.1 mm. |
| 5 cm | A few forams. |
| 10 cm | A few forams. |
| 18 cm | Diatoms rare. Forams relatively common but only 10% of sample. Include *Globigerina pachyderma* (Ehrenberg), *G. bulloides* d'Orbigny, and *Globigerinoides rubra* (d'Orbigny). One 1-mm sand grain. |
| –35 cm | A transition zone in color from reddish on top to blue gray below. Forams rare. No grains larger than 0.2 mm. |
| 127 cm | Slightly bluish, medium dark-gray "blue" mud. Less than 5% nonclay. Grains as large as 0.2 mm rare. All grains larger than 0.2 mm mentioned below. |
| 50 cm | One 1-mm rock fragment, one 0.5-mm rock fragment, but total amount of nonclay much less than 5%. A few forams. |
| 60 cm | No diatoms. Very few forams, *Globigerina pachyderma* (Ehrenberg). One 1 mm grain. |
| 80 cm | Very little silt, no sand. A few forams. |
| 100 cm | A few very fine sand grains. Forams rare. |
| 127 cm | (bottom) No diatoms. No sand. A few forams, *Globigerina pachyderma* (Ehrenberg), *G. bulloides* d'Orbigny. |

TABLE 2.—*Continued*

NH C-6 (56° 00′ N., 144° 45.8′ W., 2100 fathoms, no core, apparent depth of penetration 120 cm)
The coring tube came up empty although a coating of blue mud on the outside of the corer indi
penetration of more than a meter. Scrapings show no forams or sand grains.

NH C-7 (Axis of the Aleutian Trench, 56° 59.8′ N., 148° 49.4′ W., 2650 fathoms, 37 cm long, pene
not measured)

| | |
|---|---|
| 0–2.5 cm | Reddish-brown volcanic ash. Isotropic, index of refraction 1.487±0.001. Shards una<br>No sand, 15% silt. Diatoms rare. No forams. |
| 2.5–37 cm | Medium dark-gray "blue" mud. |
| 37 cm<br>(bottom) | No sand, a few per cent of silt. Diatoms rare. No forams. |

NH C-8 (48° 37.5′ N., 157° 29.1′ W., 2750 fathoms, core 48 cm long, depth of penetration 48 cm)

| | |
|---|---|
| 0–48 cm | Reddish-brown sandy diatom mud from top to bottom. Much more diatomaceous than bottom. |
| Top | 10% sand. Some $MnO_2$ grains. One basalt pebble 20 x 10 x 10 mm with a $MnO_2$ c perceptible but less than 1 mm thickness. One very fine-grained light-gray pebble in diameter, coated with $MnO_2$. Very abundant diatoms. No forams. |
| 10 cm | 10% sand. Some $MnO_2$ grains. |
| 13 cm | One 5-mm pebble coated with $MnO_2$. |
| 20 cm | 10% sand. $MnO_2$ grains more common. |
| 30 cm | 10% sand. One 2-mm quartz grain. |
| 40 cm | 5% sand. Largest grains 1 mm. |
| 48 cm<br>(bottom) | 15% sand. One pebble 8 mm in diameter, coated with $MnO_2$. Diatomaceous. Some laria. No forams. |

NH C-9 (48° 52.8′ N., 155° 13′ W., 2920 fathoms, 180 cm long, penetration not measured)
Reddish-brown clay throughout. No sand-sized material except $MnO_2$ flakes. Some diatoms and
laria at top and bottom. No forams.

fine-grained sandstone of quartz, feldspar, epidote, and mica, angular
black chert with minute quartz veins, well rounded.

> "How these pebbles, having all the characteristics of glacial-worn pebbles, came to be carried to this point is an interesting question. As the sharks' teeth and cetacean bones found in the red clay seem to indicate that since tertiary times there have been but very insignificant deposits at great distance from continental areas, similarly we may be tempted to assume that these pebbles, which could not have been transported to their present locality by any agency of the present epoch, were carried to it during the glacial epoch, the thin coating of manganese indicating how small have been the bottom deposits since the glacial period."

The possibility that the pebbles were kelp-rafted cannot be lightly dismissed because the area is so far south of other known glacial marine deposits. However, the uniform coating of manganese corresponds to the coating on the marine till dredged in the Gulf of Alaska, and the absence of uncoated pebbles suggests that the transporting agent is not acting at the present time. If the present general winter surface drift of the northeastern Pacific (Sverd
*al.*, 1942, Chart VII) is any indication
drift during Pleistocene time, most of the
ing ice probably was trapped in the gyral
Gulf of Alaska (Fig. 1). Nevertheless so
the larger bergs may have been swept
the south in the cool waters of the Cali
Current near shore.

Dredge hauls from five seamounts wes
southwest of southern California (Fig. 1)
the rarity of glacial marine or other raftec
ment in the vicinity of Albatross Statio
2. Many hundreds of pebbles were dredgec
Erben and Fieberling seamounts (Carsol
Dietz, 1952, p. 484), but all were basalt.
and Henderson seamounts were surveye
dredged in June 1951 from the U.S.S.
(R) 857, operated by the Navy Elect
Laboratory. All the scores of pebbles, co
and boulders recovered were basalt. Lik
dredging on San Juan Seamount (Shepar
Emery, 1941, p. 29) yielded no rock
than basalt. These dredge hauls should
contained some glacial marine sedim

ting ice was at any time common in the . The absence of such sediment suggests t the berg or bergs that rafted the pebbles nd at Albatross Station No. 2 were unusually e and long-lived, or else that the pebbles e not rafted by ice.

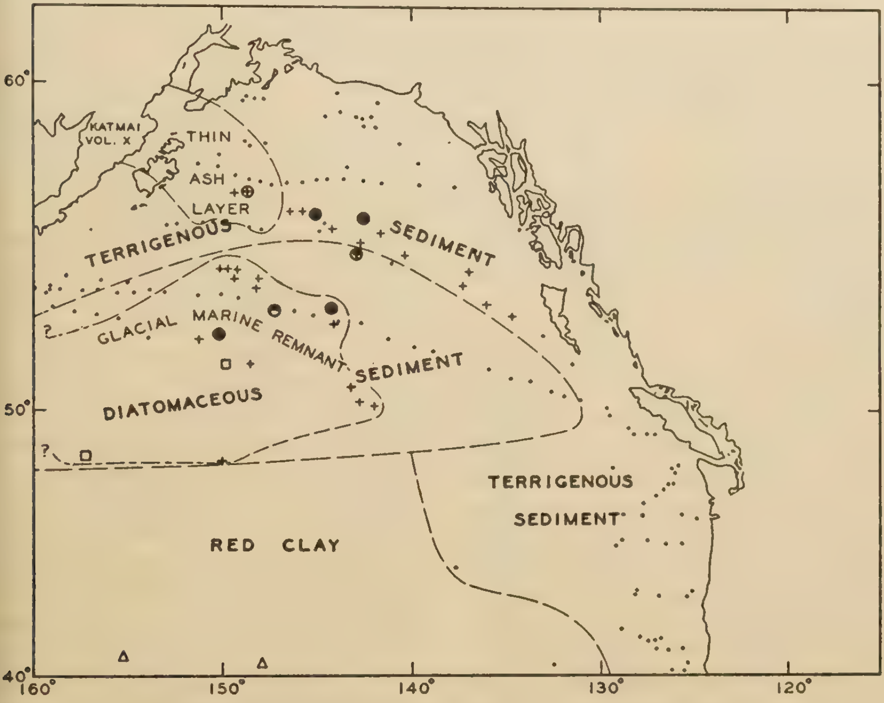

FIGURE 2.—PRESENT DISTRIBUTION OF MARINE SEDIMENT

### *Changes in Sediment Distribution*

hanges in the areal distribution of sediment es on the deep-sea floor are produced by iations in the volume of sediment introduced rivers, in the productivity of organic life, current patterns (Arrhenius, 1950), and in ticular by the presence or absence of float- ice. Some changes in distribution in the theastern Pacific are shown by the Northern liday cores, and other changes can be in- ed from cores, taken in the southern Indian an, which lie in an analagous position rela- to a glaciated area. The distribution of red , blue mud, and glacial marine sediment is tively easy to infer compared to the distri- ion of diatom ooze and diatomaceous muds ause the percentage of diatom frustules in a sediment varies with diatom productivity and solubility and also with quantity of sediment from other sources. For this reason no attempt is made to separate diatom ooze or diatom mud from diatomaceous red clay or blue mud. All sediment in which diatom frustules are an important constituent is grouped as "diatomaceous sediment."

The sediment distribution in late Pliocene time can only be inferred; presumably it included blue mud near shore, red clay in the deep open sea, and an east-west trending band of diatomaceous sediment near its present position (Fig. 2).

With the appearance of the first floating ice, marine drift began to spread over the northeastern Pacific and obscure the earlier sediment boundaries.[1] Moreover, according to Don Miller (Personal Communication) glacial marine sediment exposed along the northeastern shore of the Gulf of Alaska may be of Miocene age; if so, some Tertiary ice may have floated into the open sea. This drift is now found at or very near the surface of the sea floor only on the tops of seamounts and in the area of Cores 2, 3, and 8 (Fig. 2), but formerly it must have covered all the sea floor from the edge of the continental shelf to a southern limit at approximately 45° N. Latitude (Fig. 1). Very rarely bergs may have floated as far south as 28° N. Latitude.

---

[1] The supply of floating ice must have varied from glacial to interglacial age with in the Pleistocene Epoch, but the whole epoch will be considered as one of dominant glacial marine sedimentation for ease of discussion.

The southern limit of the zone of diatomaceous sediment spread south with increasingly cold water, and the northern limit moved south because of dilution by rapidly deposited marine drift.

Melting back of the Pleistocene glaciers from the Alaskan continental shelf freed the waters of the northeastern Pacific from floating ice and cut off the supply of marine drift. As the water warmed, the diatomaceous zone moved north, so red clay began to lap over diatom ooze, and diatomaceous sediment was deposited on the southern zone of the drift. In the Indian Ocean, likewise, a few centimeters of diatom ooze have lapped over the outer edge of the marine drift which fringes Antarctica (Murray and Philippi, 1908; Schott, 1939).

While a thin layer of diatomaceous sediment encroached from the south, a much thicker flood of blue mud began to spread out from the continental shelves over the marine till. Core 5 did not penetrate marine till although it is 127 cm long, so a relatively thick layer of fine-grained sediment has spread for a distance of at least 260 miles from the edge of the continental shelf since glacial marine sedimentation ceased. For an order of magnitude calculation, it may be assumed that floating ice disappeared from the area 10,000 to 20,000 years ago, and that the minimum rate of sedimentation has been roughly 10 cm/1000 years even at such a great distance from shore. The rapid rate of sedimentation may be attributable in part to the large amount of rock flour supplied by melting glaciers. Tyler (1931) noted that the freshness of the minerals in his samples from the Gulf of Alaska indicated little chemical decay. The blue muds in Cores 5 and 7 consist of silt- and clay-size grains, but the material appears to be an unaltered rock flour with an admixture of pelagic organic detritus.

### *Ash from Katmai Volcano*

The most recent change in deposition
in the Northern Holiday cores is shown b
occurrence of a layer of volcanic ash lying
blue mud in Core 7 (Fig. 3) taken nea
axis of the Aleutian Trench east of Ko
This core slowly extruded from the c
tube when it was brought on deck. As
truded, it was measured, and sections
placed in jars. A marked change in sed
type was noted 1 inch from the top, an
top inch was stored in a separate jar. A
time it appeared that the top layer was
uniform as to grain size and color, bu
inspection was superficial. Most of the sed
in the jars has since slumped into a sha
mass so that detailed measurements of
ness or determinations of small chang
sediment type with depth in the core ar
possible. Microscopic examination shows
the top layer is volcanic ash and that the
ment below is a blue mud like the mud in C

The general source of the ash layer i
difficult to find because a large number of a
volcanos in the Alaskan Peninsula lie up
relative to the constant west to east move
of the upper air. However, no other ash l
were observed in the underlying blue mu
it would appear that perceptible thicknes
ash were not ordinarily spread as far a
miles from the volcanoes to the positi
Core 7. On the other hand no blue mud
observed on top of the ash layer so the eru
or eruptions which produced it probabl
curred during the last few hundred y
(The rate of deposition of blue mud at C
is roughly 1 cm/100 years.) An extraordi
violent volcanic eruption within the last
dred years would appear to give the sin
explanation of the facts. The town of K
lies roughly midway between the po
source volcanoes and the location of Co
Only two ash falls have been recorded
½ inch in 1867, and 10 inches in 1912. Th
ter fall is the only likely source of the a
Core 7.

The well-known explosion of Katmai Vo
on June 6, 1912, blew about 5 cubic mi
rock into the air (Martin, 1913). Martin
numbered figure, p. 132) has drawn an
pachous map of the total thickness of ash

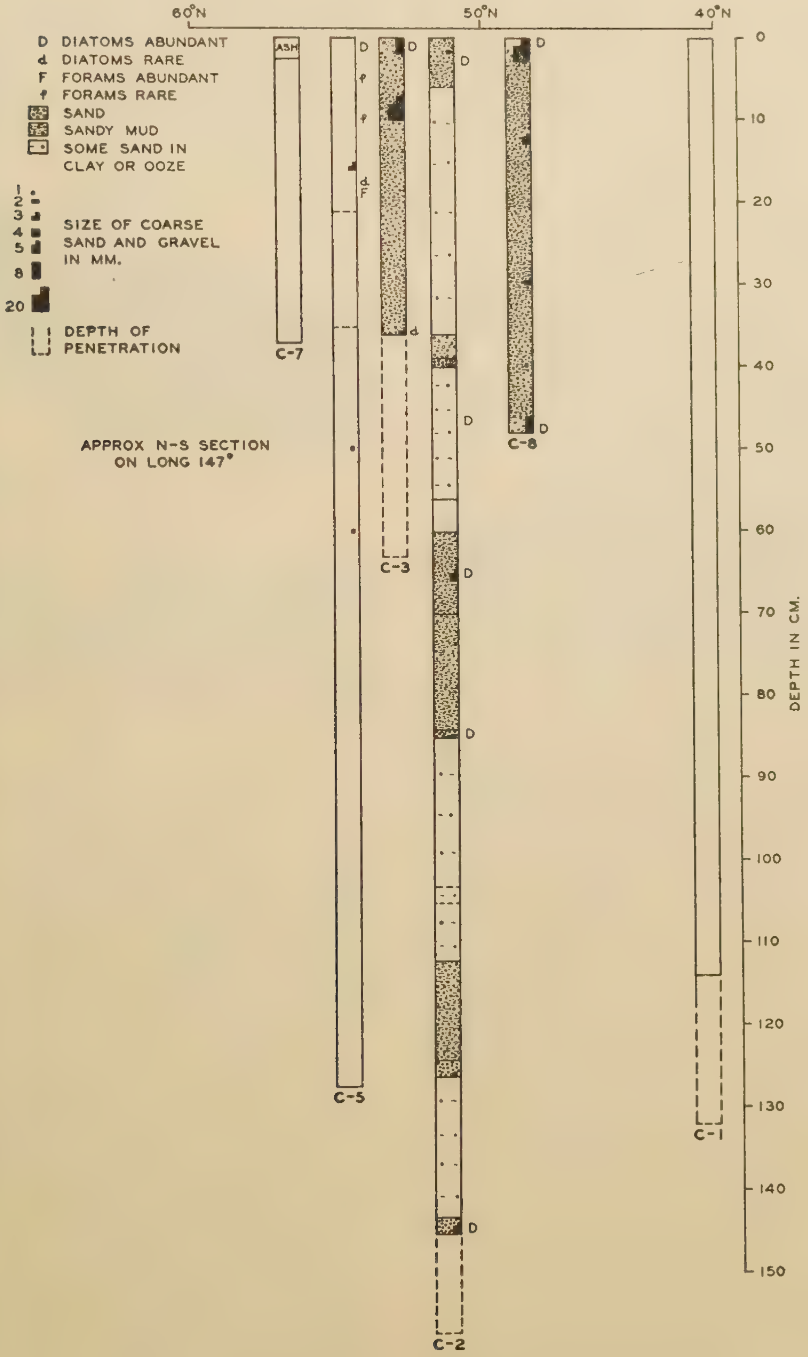
60°N
50°N
40°N
D DIATOMS ABUNDANT
d DIATOMS RARE
F FORAMS ABUNDANT
f FORAMS RARE
SAND
SANDY MUD
SOME SAND IN CLAY OR OOZE
1
2
3
4
5
8
20
SIZE OF COARSE SAND AND GRAVEL IN MM.
DEPTH OF PENETRATION
APPROX N-S SECTION ON LONG 147°
ASH
C-7
C-5
C-3
C-2
C-8
C-1
D
d
F
f
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
DEPTH IN CM.

FIGURE 3.—DISTRIBUTION OF SAND AND GRAVEL IN DEEP-SEA CORES

Katmai eruption. The contoured area is
ıgate toward the east-southeast because of
d transportation of the ash. The total thick-
; of the ash in this direction was 50 inches

at a distance of 20 nautical miles from the volcano and 10 inches at 88 miles (Kodiak). Martin had no observation points at sea beyond Kodiak, but he placed the 1-inch isopleth about

175 nautical miles east-southeast of the volcano, and the ¼-inch isopleth about 195 miles east-southeast. The ash contained three distinct layers which varied in grain size with distance from the source. The top and bottom layers were gray or gray and white, and the middle layer was brown. This brown layer appears to correspond to the reddish-brown ash layer found at the top of Core 7 not only because of color and fine grain size but because both are composed almost wholly of volcanic glass with only a small percentage of mineral fragments.

The thickness of ash in Core 7 shows that the 1-inch isopleth was fully 213 nautical miles from Katmai. Bottom-sample notations on U. S. Coast and Geodetic Survey chart no. 8502 show brown mud for some distance east of the location of Core 7 (indicated by "Thin ash layer," Fig. 2) and gray mud east of the brown mud. The sampling devices used give a more or less composite sample. If it is assumed that ¼ inch of brown ash is the minimum thickness that would be detected in a composite sample collected in routine operation, the ¼-inch isopleth probably lies about 280 nautical miles east-southeast of Katmai Volcano. These observations show that the ash distribution was more widespread than Martin (1913) believed; however, his estimate was based on the rate of thinning of the entire ash deposit, consideration of the fine brown volcanic layer alone would suggest a different distribution. The material in Core 7 contains particles no larger than 0.1 mm in diameter, and Martin describes it as "impalpable dust" on land. Its settling velocity in air is about 1.5 knots. Martin (p. 176) did not find it as a separate layer closer than 61 nautical miles from Katmai Volcano in an east-southeast direction. At this point, Uganik Island, the layer was about 1½ inches thick so it probably existed somewhat closer to the volcano although it was unobservable because of the waters of Shelikof Strait. The ash was emitted from the top of Katmai Volcano at an elevation of about a mile, but it was seen to rise to great heights before spreading under the influence of the wind. Assuming a rapid rise to a total elevation of only 3 miles, the fine brown ash would require 2 hours to reach sea level. A wind velocity of only 30 knots would spread the ash to Uganik Island before settled to the ground.

The fine brown layer at Kodiak is 4½ in thick, although the town is 27 miles fa from Katmai than Uganik Island. It w appear that the wind produced a diffused c of fine ash and that only the edge of the settled on Uganik Island whereas Kodiak closer to the center. With these facts in a distribution of brown volcanic ash on sea floor beyond the limits estimated by M would be expected.

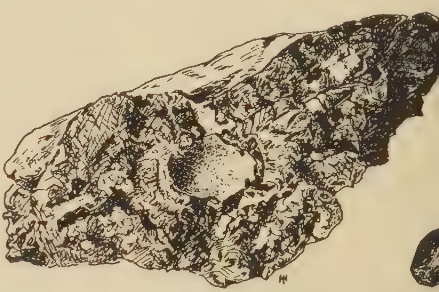

FIGURE 4.—POCKET IN A CRUST OF MANGA AND THE PEBBLE FOUND IN THE POCKET

## EVIDENCE OF DEEP CURRENTS

### *Scour on Gilbert Seamount*

Water movement deep within the oce indicated by many lines of evidence:

(1) At all depths, the sediment on topographic highs on the sea floor has winnowed of fine sediment (Shepard, p. 303).

(2) Cretaceous rocks have been dredged the tops of seamounts at depths as gre a mile—indicating prolonged nondepos caused by the sweeping action of currents

(3) Ripple-marked Globigerina ooze been photographed on the top of a sean at a depth of 750 fathoms (Menard, 195

The mode of occurrence of pebbles w the manganese crust from Gilbert Sean provides a new line of evidence that sea moves at great depth and that the movem persistent; it also gives some clues rega the current velocities required to swee tops of some seamounts free of sediment.

The pebbles are surrounded by an env

ell-sorted coarse sand containing some tests Foraminifera (Fig. 4). Most pebbles and r sand envelopes are completely incased in the manganese crust. One pebble projects ve the top of the manganese crust although sts in a smooth-sided pocket in the crust. pocket contains no sand, presumably use it fell out during the dredging. The ble itself is imbedded in manganese at its . Sand around completely inclosed pebbles so loose that it could be poured out when pockets were exposed by cutting in the ratory. The manganese around the pebbles inly laminated so that the former surface e crust at various times can be seen.

he supposed origin of the pockets in the ganese and of the sand envelope around pebbles is shown in Figure 5. The pebbles andstone, shale, basalt, and quartz and the sand and foraminiferal tests in the ets suggest that a continuous (or frequent) of ice-rafted sediment fell on the seamount. absence of sand layers or individual sand s within the manganese crust shows that of the rain of sand was swept off the th crust. Occasionally a pebble that was arge to be moved by the currents chanced ll on the crust. Slow deposition of man- se produced upward growth of the crust except near the pebble where deposition was inhibited for some reason—possibly because of increased turbulence connected with scour around the pebble. As the growth continued upward, a pocket formed around the pebble. Sand which was swept across the crust collected in the pocket where the coarser grains remained although finer grains were winnowed out as though from a pothole. Eventually the crust grew so high that the top of the pebble no longer projected above the surface, and the pebble ceased to affect the flow of currents. The crust then grew laterally and sealed off the pocket.

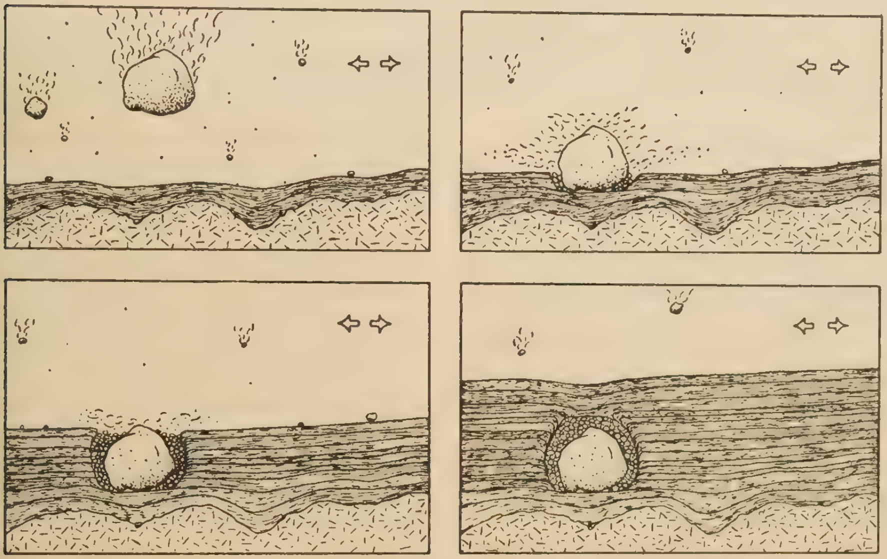

FIGURE 5.—SUPPOSED ORIGIN OF POCKETS IN A MANGANESE CRUST ON A SEAMOUNT

Experiments show that pebbles with a nominal diameter of 14.5 mm (the size is not significant in the present discussion) and various shapes require mean current velocities between 14.5 and 42 cm/sec to put them in motion if they rest on the smooth painted bed of a flume (Krumbein, 1942). If 14.5 mm pebbles rest on other pebbles of the same size, however, the current velocity required to move them is about 150 cm/sec (Hjulstrom, 1935, p. 298). These observations indicate the important effect of bed friction on competent velocity for a given size of sediment.

The manganese crust is smooth although minor irregularities probably make the bed friction higher than it is for painted wood. In the circumstances it would appear that the current velocity required to sweep coarse sand grains off the crust would be very small. The smallest pebbles found in any quantity incased in individual pockets in the manganese have a diameter of about 10 mm. The current velocity was not large enough to move these pebbles even on the smooth crust.

### *Sand Layers in Core 2*

Core 2 contains four well-sorted sand layers separated by diatomaceous ooze and mud (Fig. 3). The upper three layers are only a few centimeters thick; the bottom of the core is in the fourth layer so its thickness is not known. The core was taken in 2450 fathoms of water about 320 nautical miles from the nearest land. The sea floor was relatively flat along the HORIZON track to north and south of the position of Core 2, but Seamounts GA-14 and GA-15 (Menard and Dietz, 1951, p. 1273) are only 40 to 50 miles to the northeast.

The layers contain a mineral suite (Table 2) which closely resembles the suites identified by Tyler (1931) in samples taken nearer shore in the Gulf of Alaska. The uniformity of the minerals in all parts of the Gulf argues for a common continental source rather than local sources on the sea floor. Ice rafting probably transported the sand to the vicinity of its present position. However, the sand layers in Core No. 2 were not emplaced directly from bergs because they do not have graded bedding which would be produced by the same differences in settling velocity which would separate the sand from the finer material settling from a berg. The sand layers must be the result of reworking of the ice-rafted sediment on the deep sea floor.

The nature of the process which caused the reworking is not apparent from an examination of Core 2. Similar sand layers in the deep sea have been tentatively ascribed to the action of hypothetical slumps and turbidity currents (Bramlette and Bradley, 1940, p. 16; Kuenen, 1950, p. 240; Phleger, 1951; Shepard, 1951). The sand layers in Core 2 provide no new line of evidence to support emplacement by turbidity currents. They give yet another proof that some process transports and sorts sedimer the deep sea floor, and in the absence of other known process they are also tentat attributed to turbidity currents.

## CONCLUSION

Pleistocene changes in deep-sea sedim tion were widespread and profound just as were on the continents. As till was spread the continents by glaciers, so marine drif ice-rafted over the northeasternmost P Ocean to cover an area almost half as lar the United States. As periglacial action al sedimentation on the fringes of contin glaciers, so changes in temperature and in winds and currents altered pelagic sedi tation beyond the area of marine drift.

Post-Pleistocene changes in marine sedi tation have also resembled those on lan the forests of pine and birch migrated when the air became warmer, so the zo high diatom productivity migrated north the ocean water became warmer. As gravels and dune sands covered glacial ti blue mud and volcanic ash spread out the continent and covered most of the m drift in the northeasternmost Pacific Oce

## REFERENCES CITED

Agassiz, A, 1902, Preliminary report and l stations (ALBATROSS expedition (1899– Mus. Comp. Zoölogy Mem., v. 26, 175

Arrhenius, G., 1950, Late Cenozoic cl changes as recorded by the equatorial c system: Tellus, v. 82, p. 83–88.

Belknap, G. E. (Cdr), 1874, Deep-sea sou in the North Pacific Ocean (Tusca U. S. Hydrog. Office Pub. 54, 51 pages.

Bramlette, M. N., and Bradley, W. H., Geology and biology of North Atlantic sea cores, Pt. 1, Lithology and geolog terpretations: U. S. Geol. Survey Prof. 196-A, p. 1–32.

Carsola, A. J., and Dietz, R. S., 1952, Subr geology of two flat-topped northeast seamounts: Am. Jour. Sci., v. 250, p. 48

Emery, K. O., and Dietz, R. S., 1941, G coring instrument and mechanics of se coring: Geol. Soc. America Bull., v. 1685–1714.

Emery, K. O., and Tschudy, R. H., 1941, portation of rock by kelp: Geol. Soc. A Bull., v. 52, p. 855–862.

Flint, R. F., 1947, Glacial geology and the tocene Epoch: New York, John Wile Sons, 589 pages.

Hamilton, E. L., 1951, Sunken islands of th

Pacific Mountains (Abstract): Geol. Soc. America Bull., v. 62, p. 1502.

strom, F., 1935, Studies of the morphological activity of rivers as illustrated by the River Fyris: Univ. Upsala Geol. Inst. Bull., v. 25, p. 221–525.

gh, Jack L., 1950, Pleistocene lithology of Antarctic ocean-bottom sediments: Jour. Geology, v. 58, p. 254–260.

rographic Office, U. S. Navy, 1946, Ice atlas of the northern hemisphere: H. O. no. 550, 106 pages.

nbein, W. C., 1942, Settling-velocity and flume-behavior of non-spherical particles: Am. Geophys. Union Trans., v. 23, p. 621–632.

nen, Ph. H., 1950, Marine geology: New York, John Wiley and Sons, 551 pages.

tin, G. C., 1913, The recent eruption of Katmai Volcano in Alaska: Natl. Geog. Mag., v. 24, p. 131–181.

ard, H. W., 1952, Deep ripple marks in the sea: Jour. Sed. Petrology, v. 22, p. 3–9.

ard, H. W., and Dietz, R. S., 1951, Submarine geology of the Gulf of Alaska: Geol. Soc. America Bull., v. 62, p. 1263–1285.

ray, J., and Philippi, E., 1908, Die Grundproben der "Deutschen Tiefsee-Expedition": Wissenschaftliche Ergebnisse, "Valdivia" 1898–1899, p. 80–206.

h, B. N., 1912, Report on rock specimens dredged by the MICHAEL SARS in 1910, by H.M.S. TRITON in 1882, and by H.M.S. KNIGHT ERRANT in 1880: Royal Soc. Edinburgh Proc., v. 32, p. 262–291.

ersson, H., 1943, Manganese nodules and the chronology of the ocean floor: Goeteborgs K. Vet. Vit. Samh. Hand. Sjatte Foljden, Ser. B, Band 2, p. 1–43.

ger, F. B, 1951, Displaced Foraminifera faunas, Turbidity Currents; a symposium: Soc. Econ. Paleontologists and Mineralogists, Special Pub. no. 2, p. 66–75.

Phleger, F. B, and Parker, F. L., 1951, Ecology of Foraminifera, Northwest Gulf of Mexico: Geol. Soc. America, Mem. 46, 152 pages.

Piggot, C. S., 1941, Factors involved in submarine core sampling: Geol. Soc. America Bull., v. 52, p. 1513–1524.

Revelle, R. R., 1944, Marine bottom samples collected in the Pacific Ocean by the Carnegie on its seventh cruise: Carnegie Inst. Washington, Pub. 556, 196 pages.

Schott, W., 1939, Deep-sea sediments of the Indian Ocean, *in* Trask, P. O. (Editor) Recent Marine Sediments; a symposium, Am. Assoc. Petroleum Geologists, Tulsa, p. 396–408.

Shepard, F. P., 1948, Submarine geology; New York, Harper and Bros., 338 pages.

——, 1951, Transportation of sand into deep water, Turbidity Currents; a symposium, Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 2, p. 53–65.

Shepard, F. P., and Emery, K. O., 1941, Submarine topography off the California coast, Geol. Soc. America Special Paper 31, 171 pages.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., 1942, The oceans, New York, Prentice-Hall, 1087 pages.

Tyler, S. A., 1931, The petrography of some bottom samples from the North Pacific Ocean, Jour. Sed. Petrology, v. 1, p. 12–22.

Wooster, W. S., 1951, Operation Northern Holiday, Univ. of Calif., Scripps Inst. of Oceanography, Reference 51–46.

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# The Generation of Wind Waves on a Water Surface

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The statistical methods for treating continuous media developed lsewhere are applied to the generation of surface gravity waves. he wind stress is assumed to be everywhere normal to the isturbed surface of the water and caused by a known ensemble f "gusts." Each gust is considered to be a center of high or low ressure, which moves with the mean wind speed, and has a radius , and duration $T$. The rms value of the variable wind pressure is ssumed to vary systematically from point to point in a storm. he calculations are made for an idealized, long continuing storm; efore applying the statistical equations, the effect of a single gust calculated.

It is shown that the single gust produces a $V$-shaped wake, hich, after the gust has blown itself out ($t>T$) can be considered s a packet of free gravity waves, which moves and spreads under e influence of divergence and dispersion.

The results of the statistical calculation are compared with nown general facts, and with an actual storm. From the fact that e storm waves have a non-sinusoidal character, and arrive at ny one point in groups of 5 to 10 crests, it is deduced that the uration of a gust is from 15 to 30 seconds. From the fact that the ajority of the wave energy travels in directions that are within 0° of the wind, and with phase velocities that are nearly equal to e wind speed, the mean radius of the gusts is deduced to be out 40 meters in the case of a wind speed of 20 meters per second. The crest length of the waves is proportional to the distance $r$ from the storm, and inversely to its diameter, $D$; when $r/D=10$, the dominant length of the crests is 2.2 wavelengths.

The rms displacement, $H$, of the sea-surface from its horizontal mean is a function of the parameters already mentioned and of $P$, the rms value of the variable component of the wind pressure at the center of the storm; for the idealized storm considered, and for $r/D\gg 1$, this is approximated by

$$H^2=10P^2D^2/rL,$$

all quantities being in centimeters, including $P$, which is measured in centimeters on a water barometer. Comparison with data for an actual storm indicates that this theory requires a value of $P$ that is possibly 10 times greater than its actual value.

While the theory explains many of the phenomena of storm waves, it is therefore incapable of accounting quantitatively for the wave height. The possible reasons for this inadequacy are discussed. The relation of the theory to Jeffreys' sheltering theory is also discussed, and it is shown that both postulate that the variable component of the wind stress is normal to the water surface. The sheltering theory also postulates that the wind pressure lags 90° behind the surface disturbance. A similar phase lag is a consequence of the assumptions of the present theory.

## 1. INTRODUCTION

THE mechanism by which a wind blowing over a water surface produces gravity waves is not well nderstood. During the past ten years, much new ob- rvational material has been accumulated and sum- arized in useful semi-empirical relations.[1,2] The start- g point of this analysis has been the equations of free, nusoidal, infinitesimal, and irrotational surface waves. hat each of the four adjectives represents an over- mplification is clear, and the necessity for modifying e equations before they will conform to the observed enomena is not to be interpreted as a failure of any the basic equations of hydrodynamics.

The present paper develops a theory of forced, non- usoidal, but infinitesimal and irrotational surface aves. The term "infinitesimal," in this connection, fers to the neglect of nonlinear terms in the hydro- namic equations; it seems certain that this must timately be remedied if all phenomena connected with e interaction of wind and water are to be treated eoretically. However, there are some that appear to largely independent of the nonlinear terms, and it is erefore justified to retain this simplification for the time being. Much the same can be said about the simplifying assumption of irrotationality.

Since the wind exerts forces on the water, wind-waves are not free, by definition. This has been recognized in the past by dividing the problem into two: waves in the generating, or storm area, and waves in the relatively calm or decay area at a distance from the storm. In the decay area, the equations of free waves can certainly be justified: this will appear in Sec. 8 below. The primary problem in this region is not the transfer of energy from air to water, but rather the relation between the free waves and the forces that generated them at an earlier time.

In the generating area the waves may be many meters high, and thus represent a large surface density of energy. This energy cannot be supposed to have been obtained from the air instantaneously and locally. Much of it will have been obtained from the air earlier and at a considerable distance from the point of observation (though still in the storm area). It will have been transported by the water essentially according to the laws of free wave motion. This has long been recognized by the use of the concept of *fetch*, introduced more or less empirically into the theory. In Sec. 7 a definite integral will be encountered that corresponds fully with this concept and enables certain of its aspects to be clarified. It is in many ways analogous to the concept of *optical depth* in theories of scattering and visibility.

From what has been said, it is to be expected that the equations of free wave motion will be useful even in the storm area: in Sec. 7, it will be shown that this is a consequence of an approximation justified by preliminary considerations given in Sec. 5. It is not to be supposed, however, that the forces of the wind can be completely neglected and that the equations of free wave motion can be used from the beginning. For this reason, the rather lengthy development in the earlier sections is unavoidable.

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* On leave from the Scripps Institution of Oceanography. This SIO Contribution No. 648 (New Series).

H. U. Sverdrup and W. H. Munk, *Wind, Sea, and Swell:* eory of Relations for Forecasting, (U. S. Navy Hydrographic ice Publication No. 601, 1947).

C. L. Bretschneider, Trans. Am. Geophys. Union **33**, 381 52).

In these sections the wind stress is treated as a function of space and time that is known, at least in a statistical sense. One limitation on this force is imposed by the decision to consider only irrotational motion: it must everywhere be normal to the air-water interface. Since this surface is inclined, the wind-stress may have a horizontal component (see Sec. 10) but any tangential component would generate vorticity, and must therefore be neglected in order to remain consistent with the previous decision.

This is perhaps unfortunate, for as a result of the empirical analysis of wind-sea phenomena, it is generally considered that the tangential stress is not negligible.[1] The possibility of introducing tangential stresses into the theory of wave generation has been considered by Jeffreys.[3] The solutions of his differential equations did not conform to the facts, and he therefore abandoned them in favor of a theory that considers only normal pressures. While following Jeffreys in this, the present calculation differs from his in another important respect.

Surface waves can be caused only by a variable pressure, since a constant atmospheric pressure merely adds to the hydrostatic pressure in the water without deforming the surface. Jeffreys supposes that the variable component of the wind pressure is caused by the waves already present (see above) and that there would be no variable wind pressure if the air-water interface were perfectly flat. Specifically, he supposes that the wind pressure is 90° out of phase with the sinusoidal waves, so that the pressure on the up-wind side of a crest is greater than on the down-wind side. The quantitative relation between this pressure and the wind speed and the slope and velocity of the crest is formulated in terms of the constant known as the sheltering coefficient.[4]

In the following, no such relation will be assumed. Instead, it will be supposed that the wind pressure (even on a flat horizontal surface) has a variable component. This is considered to be the result of moving centers of high (or low) pressure, as described in Sec. 3. These centers, or gusts, are assumed to move with the mean wind speed. It is shown, in Secs. 5 and 8, that this one assumption explains many of the facts used by Jeffreys in constructing his sheltering theory. Finally, in Sec. 10, it is shown that there is a phase difference between the wind pressure and the surface waves whi it causes, which results in a horizontal component of t wind pressure the time average of which does not vanis The present theory is therefore a kind of inverse of t sheltering theory—inverse with regard to cause a effect.

Crucial experiments are difficult to perform in area where large storm waves are being generated, b there is some evidence for the existence of pressu fluctuations capable of producing waves on an und turbed water surface.† Observations were made[5] on small pool, in a location where the early morning is oft a period of dead calm with a thermally stable atmo phere. As the ground is heated by the sun, small cente of convection are apparently produced in the air, a as these move across the previously mirror-flat surfa of the pool, they cause ripples and waves having t typical *V*-shaped configuration of a wake. The theory such wakes is similar to that of Lambs' "fish-line pro lem"[6] and it is readily seen that their most promine components are short-period gravity waves (not surfa tension ripples, although these are present also). Wh the wind reaches the "catspaw" stage, the observatio suggest that the surface of the pool is simultaneous subjected to a multitude of pressure centers.

There is also evidence which suggests that the d turbance caused by higher winds on a somewhat larg body of water consists of such wakes. The observatio were made on a nearly rectangular pond, 240 m 60 m, and 2 m deep: ". . . at all winds, one had t impression that, in contrast to the conventional pictu of . . . waves advancing before the wind, there we instead two sets of waves, to the right and left of t wind-direction. Moreover, the angle between the wi direction and wave travel appeared to depend on wi speed, being initially about 75° and decreasing to minimum of about 15° at the highest winds observed.

On still larger bodies of water, it is probable that t pressure centers or gusts of wind will "blow themselv out", leaving their wakes to dissipate as free gravi waves under the influence of divergence and dispersic The theory of this phenomenon, for a single gust, is t subject of Secs. 2, 5, and 6.

Perhaps the most certain part of the following calcul tion, which is least likely to require modification wh the simplifying assumptions are dropped, is the stat tical treatment of the wind stress and the sea surfa This is accomplished by means of a general formu developed elsewhere,[8] and which will merely be su marized here. The basic statistical device is that of t time average, as commonly used in the theory turbulence. Let $h(x, y, t)$ be the displacement of the sea-surface, then the symbol $\langle hh'|\tau\rangle$ is defined by

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[3] H. Jeffreys, Proc. Roy. Soc. (London), **A107**, 189 (1925).

[4] See reference 3. This theory is also discussed in H. Lamb *Hydrodynamics* (Cambridge University Press, Cambridge, 1932), sixth edition, p. 625, as well as in Reference 1.

† However, see the discussion of Eq. 52.1.

[5] By G. C. Ewing; the writer is indebted to him for permission quote his unpublished observations.

[6] See Reference 4, p. 468; it should be noted that the essen feature of this problem is not the small diameter of the fish-li but its low velocity relative to the water.

[7] W. G. Van Dorn, *Wind Stress over Water*, dissertation, Scri Institution of Oceanography, (1952) Reference No. 52-60.

[8] C. Eckart, Phys. Rev. **91**, 784 (1953).

$$\langle hh'|\tau\rangle = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} h(x, y, t)h(x', y', t-\tau)dt,$$

and is the correlation of $h$ at the two points $xy$ and $x'y'$, delayed by the interval $\tau$. Similarly

$$\{hh'|\tau\} = \int_{-\infty}^{\infty} h(x, y, t)h(x', y', t-\tau)dt$$

is the delayed convolution of $h$ at the two points. It can be seen that, if the correlation of $h$ is finite, its convolution will diverge; and if the convolution is finite, the correlation will be zero. The solutions of Eqs. (1) to (5) below therefore fall into two classes: class A, for which the correlation is finite, and class I, for which the convolution is finite.

If the sea surface is idealized as a statistically steady phenomenon, the appropriate solution will be of class A. The difficulty is that the appropriate solution is then not easily obtained; those solutions of the equations that are furnished by the usual Fourier integral methods are all of Class I. This, however applies to the function $h$ itself; it can be shown that its correlation $\langle hh'|\tau\rangle$ satisfies certain other equations, whose solutions are readily exhibited. Let $h_{\mathbf{q}}$ be a family (ensemble) of class I solutions of the Eqs. (1) to (5); in the present case, $h_{\mathbf{q}}$ will be the surface disturbance produced by a single gust centered at the point $\mathbf{q}$. Then it is at least very probable that the correlation of the disturbance $h$ produced by a large number of such gusts distributed at random through space and time will be given by

$$\langle hh'|\tau\rangle = \int w(\mathbf{q})\{h_{\mathbf{q}}h_{\mathbf{q}}'|\tau\}d\mathbf{q},$$

where $w(\mathbf{q})$ is a positive function of $\mathbf{q}$—the distribution function of the gusts in space. Their distribution in time is to be such that the correlation exists. A very similar equation will connect the wind pressure of a single gust to the correlation of the pressure due to the whole random ensemble of gusts which makes a storm.

## 2. THE BASIC EQUATIONS

It will be supposed that the water can be treated as a non-viscous incompressible fluid, and that the wind pressure, $a$, is given, at least in a statistical sense. It will be convenient to express all pressures in cm of water-barometer so that the wind pressure in dynes/cm² is $\rho g a$, $\rho$ being the density of water, and $g$ the acceleration of gravity. Similarly, let $g\phi$ be the velocity potential; then, if the positive $z$-axis is vertical and upwards,

$$\nabla^2\phi = 0 \quad \text{when} \quad z<0; \tag{1}$$

$$\nabla\phi,\ \phi\to 0 \quad \text{as} \quad z\to-\infty; \tag{2}$$

$$\frac{\partial^2\phi}{\partial t^2} + g\frac{\partial\phi}{\partial z} = \frac{\partial a}{\partial t} \quad \text{at} \quad z=0. \tag{3}$$

Since no initial conditions are specified, these equations do not uniquely define $\phi$, and the condition of outgoing waves must be added to complete the formulation of the problem.

The primary interest centers on the free surface: let its equation be

$$z = h(\mathbf{x}, t), \tag{4}$$

where here, as throughout the following, $\mathbf{x}$ is the two-dimensional horizontal vector whose components are $x, y$. Then $h$ may be obtained from

$$h(\mathbf{x}, t) = (\partial\phi/\partial t)_{z=0} - a(\mathbf{x}, t). \tag{5}$$

## 3. THE WIND PRESSURE

It is supposed that the wind pressure can be represented by an ensemble of gusts, $a_{\mathbf{q}}(\mathbf{x}, t)$, so that its correlation is

$$\langle aa'|\tau\rangle = \int w(\mathbf{q})\{a_{\mathbf{q}}a_{\mathbf{q}}'|\tau\}d\mathbf{q}, \tag{6}$$

$w$ being the weight function of the ensemble. For simplicity, it is supposed that the gusts are all identical except for the location of their centers, and that these have the coordinates $\mathbf{q}$, so that

$$a_{\mathbf{q}}(\mathbf{x}, t) = a_0(\mathbf{x}-\mathbf{q}, t). \tag{7}$$

The function $a_0$ is to be real, and such that it can be represented by the Fourier integral

$$a_0(\mathbf{x}t) = \int\int A(\mathbf{k}\omega)\exp[i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\mathbf{k}d\omega, \tag{8}$$

the integration over $\omega$ and the two components of $\mathbf{k}$ running from $-\infty$ to $\infty$.

Then, by the Parseval theorem,

$$\{a_0a_0'|\tau\} = 2\pi\int\int\int A(\mathbf{k}\omega)A^*(\mathbf{k}'\omega) \times\exp[i(\mathbf{k}\cdot\mathbf{x}-\mathbf{k}'\cdot\mathbf{x}'-\omega t)]d\mathbf{k}d\mathbf{k}'d\omega \tag{9}$$

and the evaluation of the integral in Eq. (6) can be simplified by introducing the function

$$W(\boldsymbol{\alpha}) = \int\int w(\mathbf{q})\exp(-i\boldsymbol{\alpha}\cdot\mathbf{q})d\mathbf{q}/(2\pi)^2, \tag{10}$$

so that

$$\langle aa'|t\rangle = (2\pi)^3\int\int\int W(\mathbf{k}-\mathbf{k}')A(\mathbf{k}\omega)A^*(\mathbf{k}'\omega) \times\exp[i(\mathbf{k}\cdot\mathbf{x}-\mathbf{k}'\cdot\mathbf{x}'-\omega\tau)]d\mathbf{k}d\mathbf{k}'d\omega. \tag{11}$$

The change of variables

$$\mathbf{r} = \tfrac{1}{2}(\mathbf{x}+\mathbf{x}'), \quad \boldsymbol{\xi} = \mathbf{x}-\mathbf{x}', \qquad \mathbf{m} = \tfrac{1}{2}(\mathbf{k}+\mathbf{k}'), \quad \boldsymbol{\alpha} = \mathbf{k}-\mathbf{k}', \tag{12}$$

reduces this to

$$\langle aa'|t\rangle = (2\pi)^3\int\int\int W(\boldsymbol{\alpha})A(\mathbf{k}\omega)A^*(\mathbf{k}'\omega) \times\exp[i(\boldsymbol{\alpha}\cdot\mathbf{r}+\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau)]d\boldsymbol{\alpha}d\mathbf{m}d\omega. \tag{13}$$

It will appear below that $W$ is appreciable only for very small values of the components of $\boldsymbol{\alpha}$, so that $\mathbf{k}$ and $\mathbf{k}'$ may both be replaced by $\mathbf{m}$ in the factors $A$ and $A^*$. The integration over $\boldsymbol{\alpha}$ can then be carried out by the inverse of Eq. (10) and

$$\langle aa'|\tau\rangle = (2\pi)^3 w(\mathbf{r}) \int\int |A(\mathbf{m}\omega)|^2 \times \exp[i(\mathbf{m}\cdot\boldsymbol{\xi}-\omega t)]d\mathbf{m}d\omega. \quad (14)$$

Setting $\boldsymbol{\xi}=0$, $\tau=0$, one obtains the mean square wind pressure in the form

$$\langle a^2\rangle = (2\pi)^3 w(\mathbf{r}) \int\int |A(\mathbf{m}\omega)|^2 d\mathbf{m}d\omega.$$

If $a_0$ is normalized so that

$$(2\pi)^3 \int\int |A|^2 d\mathbf{m}d\omega = 1, \quad (15)$$

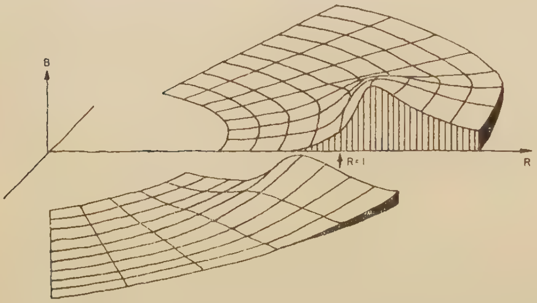

FIG. 1. The function $B$ in its dependence on $R$ and $\theta$, for $\mathcal{T}=10$, $\mathfrak{L}=3$. $R$ is the distance from the center of the disturbance, $\mathcal{T}$ its duration, $\mathfrak{L}$ its radius, all in non-dimensional form. The angle $\theta$ is the direction relative to the motion of the gust, and $B$ is the amplitude of the disturbance.

this becomes

$$\langle a^2\rangle = w(\mathbf{r}) \quad (16)$$

and furnishes a concise interpretation of the weight function $w$. Moreover, if the extent of the storm, i.e., of the region over which $w$ is different from zero, is large compared to a single gust, and if $w$ varies only slowly in this region, this justifies the approximation leading to Eq. (14).

The quantity

$$\Psi = (2\pi)^3 |A(\mathbf{m}\omega)|^2 \quad (15.1)$$

may be called the spatio-temporal spectrum of the wind pressure. It represents an analysis of this pressure into elementary waves of frequency $\omega$, wave number $\mathbf{m}$, and phase velocity $\omega/m$. These waves therefore do not all have the same phase velocity, but all velocities are represented. It may be remarked that the factorization of $\langle aa'|\tau\rangle$ into the product of $w$ and the integral over $\Psi$ is somewhat artificially introduced by the assumption that the gusts are all identical except for their centers. A more realistic assumption would have them differing in other respects as well, and the factorization woul no longer be possible.

### 4. A SPECIAL EXAMPLE

Thus far, no special properties of the function $a_0$ hav been specified. It will now be supposed that each gus consists of a pressure area (either high or low) tha moves with the mean wind.[9] To an observer movin with this same velocity $\mathbf{U}$, the gust would have a fixe center, a radius $L$, and a duration $T$. In stationar coordinates, it might be represented by the function

$$a_0(\mathbf{x}, t) = \text{const.} \exp\{-\tfrac{1}{2}[(\mathbf{x}-\mathbf{U}t)^2/L^2+t^2/T^2]\}. \quad (17$$

Then $A$ is found to be

$$A(\mathbf{k}\omega) = b \exp\{-\tfrac{1}{2}[k^2L^2+(\omega-\mathbf{k}\cdot\mathbf{U})^2T^2]\}, \quad (18$$

and in order to satisfy Eq. (15), it is seen that

$$(2\pi)^3 b^2 = L^2T/\pi^{\frac{3}{2}}. \quad (19$$

The Eq. (14) then becomes

$$\langle aa'|\tau\rangle = w(\mathbf{r}) \exp\{-\tfrac{1}{4}[(\boldsymbol{\xi}-\mathbf{U}\tau)^2/L^2+\tau^2/T^2]\}. \quad (20$$

The function $w$ will also be specialized:

$$w(\mathbf{r}) = P^2 \exp(-\tfrac{1}{2}r^2/D^2); \quad (21$$

the constant $P$ is the rms value of the wind pressure a the center of the storm, whose radius is $D$. It follow from Eq. (21) that

$$W(\boldsymbol{\alpha}) = (P^2D^2/2\pi) \exp(-\tfrac{1}{2}\alpha^2D^2). \quad (22$$

### 5. THE SURFACE WAVES CAUSED BY A SINGLE GUST

It is next necessary to obtain the solution of Eqs. (1 to (5) inclusive, when $a$ is replaced by $a_0$. Using th abbreviation

$$\kappa = \omega^2/g, \quad (23$$

this is given by

$$g\phi_0 = \Re \int\int\int 2\omega A(\mathbf{k}\omega) \exp[-i\sigma(k-\kappa) + i(\mathbf{k}\cdot\mathbf{x}-\omega t)+kz]d\mathbf{k}d\omega d\sigma, \quad (24$$

where the integrations with respect to $\omega$ and th auxiliary variable $\sigma$ both run from 0 to $+\infty$ only. Car must be exercised in the order of integration, since th integral is conditionally convergent. This is of con siderable physical significance, for it endows the integra with a protean ability to enter into the description of very diverse set of phenomena. That Eq. (24) gives solution of Eqs. (1) and (2) is clear; that $\phi_0$ also satisfie Eq. (3) is most readily seen by substituting from Eq (24) into the left of Eq. (3). The integration over $\sigma$ ca then be performed first, and the result is the time deriv ative of the right side of Eq. (8). That $\phi_0$ satisfies the condition of outgoing waves, will become clear below (Eq. (26)).

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[9] In light winds, the velocity of the gusts may be quite differen from that of the mean wind. In well developed advection, ther seems no good reason to suppose that the gusts move with velocity appreciably different from that of the mean wind at, sa 10 meters elevation.

It then follows from Eq. (5) that the surface displacement caused by the single gust is

$$h_0=\Re\int\int\int(-2ik)A(\mathbf{k}\omega)\exp[-i\sigma(k-\kappa)+i(\mathbf{k}\cdot\mathbf{x}-\omega t)]d\mathbf{k}d\omega d\sigma. \quad (25)$$

These integrals represent the solution for all values of $\mathbf{x}$ and $t$, including values near the origin, where the wave motion is not free, but forced by the wind pressure. For many purposes, it is convenient to have an approximate solution, valid only in regions of space and time where $a_0$ is negligible. Such an approximation can readily be obtained by the method of stationary phase, and is (using Eq. (18))

$$h_0=0 \quad \text{when} \quad t\ll T; \quad (26.a)$$

$$h_0=[2^{7/2}\pi^2 b/L^2 t]B\sin(\kappa_0 r-\omega_0 t) \quad (26.b)$$

when $t\gg T$ and $r\gg L$. In this equation,

$$B(\omega_0\theta)=\kappa_0{}^2L^2\exp[-\tfrac{1}{2}\kappa_0{}^2L^2-\tfrac{1}{2}(\omega_0-\kappa_0 U\cos\theta)^2T^2], \quad (27)$$

where $r=|\mathbf{x}|$, and $\theta$ is the angle between $\mathbf{x}$ and $\mathbf{U}$, while $\omega_0$ is to be determined from the group velocity equation

$$r=(g/2\omega_0)t=\tfrac{1}{2}c_0 t. \quad (28)$$

Here $c_0$ is the phase velocity, and $\tfrac{1}{2}c_0$ the group velocity of gravity waves of frequency $\omega_0$.

While $B$ is, in the first instance, a function of $\omega_0$ and $\theta$, it becomes a function of $r/t$ because of Eq. (28). For fixed $t$, its dependence on $r$ and $\theta$ determines the instantaneous amplitude of the waves on the surface of the sea. It is convenient to express $B$ in terms of the dimensionless variable

$$R=2r/Ut=g/\omega_0 U=c_0/U, \quad (29)$$

which may be interpreted as the distance traveled by the waves, as their period, or as their phase velocity, all in dimensionless form. Also introducing the dimensionless parameters

$$\mathcal{L}=gL/U^2, \quad \mathcal{T}=gT/U, \quad (30)$$

Eq. (27) becomes

$$B(R,\theta)=(\mathcal{L}^2/R^4)\times\exp\{-\tfrac{1}{2}[\mathcal{L}^2+\mathcal{T}^2(R-\cos\theta)^2]/R^4\}. \quad (31)$$

## 6. DISCUSSION OF THE AMPLITUDE FUNCTION

Figures 1 and 2 show $B$ as a function of $R$ and $\theta$ for wo sets of values of $\mathcal{L}$ and $\mathcal{T}$. It will be found that this unction dominates the remainder of the theory, and a omewhat detailed analysis of its characteristics is herefore justified. The most prominent characteristic isible on Figs. 1 and 2 is the maximum that occurs for a ertain value of $R$, when $\theta$, $\mathcal{L}$, and $\mathcal{T}$ are fixed. The position of this maximum is determined by the roots of the equation

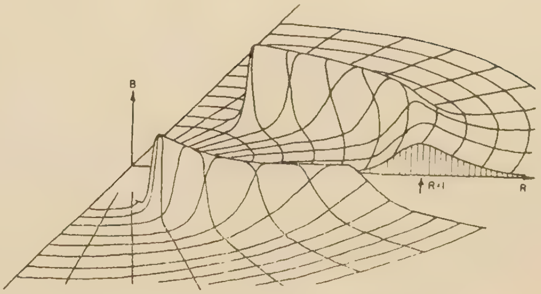

FIG. 2. Same as Fig. 1, but for $\mathcal{T}=10$, $\mathcal{L}=\tfrac{1}{4}$.

$$M+4N(u-1)(u-2)-2u^4=0, \quad (32)$$

in which

$$u=R/\cos\theta, \quad M=\mathcal{L}^2/\cos^4\theta, \quad N=\mathcal{T}^2/8\cos^2\theta. \quad (33)$$

Figure 3 is a Runge diagram[10] of Eq. (32). The coordinates of a general point $P$, in the diagram are $M$, $N$, and the roots of Eq. (32) are found by drawing tangents from $P$ to the solid curve. The value of $u$ is determined by the point of tangency, as marked on the curve. If $\mathcal{L}$ and $\mathcal{T}$ are kept fixed, and $\theta$ is allowed to increase from 0 to $\pi/2$, $P$ will move away from the origin along a parabola, as shown by the dotted curve. The corresponding change in any of the roots of Eq. (32) is readily visualized. If the point $P$ is chosen at random in the first quadrant, there is seen to be a high probability that a root of Eq. (32) will occur either very close to $u=1$ or very close to $u=2$. If $\theta=0$, $u=R$ and reference to the preceding section shows that $R=1$ corresponds to waves whose *phase* velocity is $U$, while $R=2$ corresponds to waves whose *group* velocity is $U$.

If the root lies near $u=1$, the following formula is

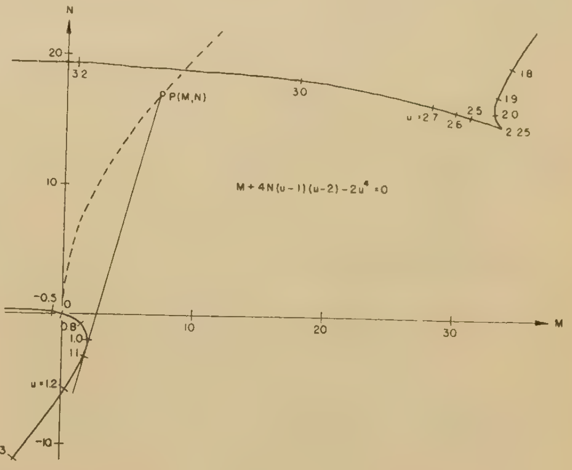

FIG. 3. A tangent from the point $P(M,N)$ to the solid curve determines one of the roots of the equation $M+4N(u-1)(u-2)-2u^4=0$, in accordance with the scale marked on the curve. The dotted parabola is the locus of $P(M,N)$ as the angle $\theta$ varies.

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[10] F. Klein *Elementary Mathematics from an Advanced Standpoint* (Dover Publications, New York, 1939), pp. 90–94.

available:

$$u=1+[(M-2)/4(N+2)]+\cdots, \tag{34}$$

while if it is near $u=2$

$$u=2+[(M-32)/4(N-16)]-\cdots. \tag{35}$$

These considerations determine the location of the extrema of $B$; the variation of their magnitudes as $\theta$ changes is determined largely by the factor

$$B_m=(\mathcal{L}^2/\mathcal{R}^4)\exp(-\tfrac{1}{2}\mathcal{L}^2/\mathcal{R}^4).$$

Since $u$ usually remains nearly constant as $\theta$ varies, $B_m$ will diminish rapidly with decreasing $\cos\theta$ provided that $\mathcal{L}$ is large, as in Fig. 1. If $\mathcal{L}$ is small as in Fig. 2, $B_m$ will at first increase, until $\cos\theta$ becomes less than a critical value, after which it rapidly approaches zero. This then manifests itself by the appearance of a prominent ridge, the projection of which on the $R, \theta$ plane nearly coincides with the circle of unit diameter and center at $R=\frac{1}{2}$, $\theta=0$.

Further insight into Figs. 1 and 2 can be obtained as follows, if only the case of roots near $u=1$ is discussed. These figures apply only to the disturbance at great distances (in time and space) from the wind gust that produces it. The first effect of the gust must be to produce a typical, V-shaped wake, as discussed in the Introduction. When the gust has "blown itself out," the further development of this wake will be that of free waves, and the combined effect of divergence and dispersion will be to resolve it into its spatio-temporal spectrum. Now it is characteristic of the elementary theory of wakes to suppose that $\mathcal{T}=\infty$, $\mathcal{L}=0$, and that their sinusoidal components are all described by $u=1$. According to this elementary theory, therefore, Figs. 1 and 2 should simply show cylinders of unit diameter, with axes at $R=\frac{1}{2}$, $\theta=0$. The departure from such knife-edge ridges is caused by the finite radius and duration of the gust.

While Eq. (31) is not elaborate, considered from the standpoint of numerical evaluation, it is difficult to integrate, even approximately. A somewhat more tractable expression, which corresponds to Eq. (34), is

$$B=M\exp\{-\tfrac{1}{2}[M+8(N+2)(u-1)^2]\}. \tag{36}$$

## 7. THE CORRELATION OF THE SURFACE WAVES

Since Eq. (25) is the rigorous expression for the waves caused by a single gust, the correlation of the storm waves may now be calculated in a manner entirely analogous to Sec. 3, though the integrals involved are more elaborate. The starting point is the ensemble

$$h_{\mathbf{q}}=h_0(\mathbf{x}-\mathbf{q},t) \tag{37}$$

and the ensemble integral

$$\langle hh'|\tau\rangle=\int w(\mathbf{q})\{h_{\mathbf{q}}h_{\mathbf{q}}'|\tau\}d\mathbf{q}. \tag{38}$$

Proceeding as in Eqs. (9) to (13):

$$\langle hh'|\tau\rangle=\mathcal{R}\int\int\int\int\int 2m^2\Psi(\mathbf{m}\omega)W(\boldsymbol{\alpha})$$
$$\times\exp\{i[-\sigma(k-\kappa)+\sigma'(k'-\kappa)+\boldsymbol{\alpha}\cdot\mathbf{r}+\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau]\}$$
$$d\boldsymbol{\alpha}d\mathbf{m}d\omega d\sigma d\sigma'; \tag{39}$$

in order to carry out the integration over $\alpha$, the further approximations

$$k,k'=m\pm\tfrac{1}{2}\boldsymbol{\alpha}\cdot\mathbf{m}_1,\quad \mathbf{m}_1=\mathbf{m}/m, \tag{40}$$

are permissible and, together with the change of variables

$$v=\sigma-\sigma',\quad s=\tfrac{1}{2}(\sigma+\sigma'), \tag{41}$$

leads to

$$\langle hh'|\tau\rangle=\mathcal{R}\int\int\int\int 2m^2\Psi(\mathbf{m}\omega)w(\mathbf{r}-s\mathbf{m}_1)$$
$$\cdot\exp\{i[-v(m-\kappa)+\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau]\}d\mathbf{m}d\omega dv ds, \tag{42}$$

the integration over $v$ extending from $-2s$ to $+2s$, and that over $s$, from 0 to $+\infty$. The integration over $v$ can be performed at once, and results in

$$\langle hh'|\tau\rangle=\int\int\int 4m^2\Psi(\mathbf{m}\omega)w(\mathbf{r}-s\mathbf{m}_1)$$
$$\cdot\{\sin[2s(m-\kappa)]/(m-\kappa)\}\cos(\mathbf{m}\cdot\boldsymbol{\xi}-\omega\tau)d\mathbf{m}d\omega ds.$$

When the point $\mathbf{r}$ is outside the storm area, the factor $w$ will have appreciable values only for very large values of $s$; the factor immediately following $w$ will correspondingly have appreciable values only when $m-\kappa$ is very small. Except in this factor, $m$ may therefore be replaced by $\kappa$. When the point $\mathbf{r}$ is in the storm area, the first step of this argument fails; closer study shows that the conclusion remains valid, because the effect of the few nearby gusts (for which $s$ is small) is negligible compared to the many distant gusts for which $s$ is large. This is true, of course, only when the dimension, $D$, of the storm is much greater than that of the single gust, $L$.

The integration $d\mathbf{m}$ may be resolved into $mdmd\vartheta$, $m$ being the magnitude of $\mathbf{m}$, and $\vartheta$ the angle between $\mathbf{m}$ and $\mathbf{U}$. After replacing $m$ by $\kappa$ everywhere except in the one factor, the integration over $m$ can be performed leading to

$$\langle hh'|\tau\rangle=4\pi\int\int\kappa^3\Phi(\omega\vartheta)S(\mathbf{r}\vartheta)$$
$$\cdot\cos[\kappa(\xi\cos\vartheta+\eta\sin\vartheta)-\omega\tau]d\vartheta d\omega, \tag{43}$$

where

$$\Phi(\omega\vartheta)=\Psi(\kappa\mathbf{m}_1,\omega)$$

and

$$S(r\vartheta)=\int_0^\infty w(x-s\cos\vartheta,y-s\sin\vartheta)ds \tag{44}$$

while $\xi$, $\eta$ are the components of $\boldsymbol{\xi}$, $xy$ those of $\mathbf{r}$.

Comparing Eq. (43) with the analogous Eq. (14) for the wind pressure, several differences become apparent. In Eq. (43), the integration is only over $\vartheta$, the direction of **m**, while in Eq. (14) the integration is also over the magnitude of $m$. The wind pressure is composed of waves of all phase velocities, while those composing the surface disturbance all have the velocity $\omega/\kappa=g/\omega$ characteristic of free gravity waves of frequency $\omega$.

Instead of the integration over $m$, the Eq. (43) contains the function $S$, which is an integral of the factor $w$ that appears outside the integral of Eq. (14). The correlation of $h$ at **r** depends, not on the local intensity of the wind disturbance at **r**, but on the integral of this intensity over the "fetch"—i.e., over the path by which waves‡ traveling in the direction $\vartheta$ reach the point **r**. The function $S$ may be called the fetch intensity.

The expression for $S$ can be obtained explicitly if $w$ is given by Eq. (21); let $\bar{x}\bar{y}$ be the components of **r** parallel and perpendicular to the direction $\vartheta$: then

$$S(r,\vartheta)=(\pi/2)^{\frac{1}{2}}P^2D\exp(-\tfrac{1}{2}\bar{y}^2/D^2)\operatorname{erfc}(+\bar{x}/2^{\frac{1}{2}}D). \quad (45)$$

If $\bar{y}=0$, the fetch passes through the center of the storm and $S$ is given by the error-function alone; if $\bar{y}\neq 0$, the fetch passes to one side of the point of maximum wind-pressure, and $S$ is correspondingly reduced by the exponential factor. If $\bar{x}\ll -D$, the error function will be practically zero: no waves are propagated backwards along the fetch. If $\bar{x}\gg D$ the point **r** is outside the storm-area, but in a down-wind direction, and the error-function will be practically equal to 2.

The disturbance at any point **r** will thus consist of free gravity waves of all frequencies and directions, each elementary wave having the intensity $4\pi\kappa^3\Phi S$ appropriate to its period and fetch. This product is the spatio-temporal spectrum of the waves, and should be compared with that of the wind, given by Eq. (15.1).

## 8. THE WAVES OUTSIDE THE STORM AREA

The further evaluation of the integral in Eq. (43) for points with large positive $\bar{x}$ can be accomplished by setting the error function in Eq. (45) equal to 2. If $\psi$ is the angle between **r** and **U**, $\bar{y}$ will be zero when $\vartheta=\psi$, and the exponential in Eq. (45) will diminish rapidly or increasing $|\vartheta-\psi|$. An estimate of $\langle hh'|\tau\rangle$ is thus obtained by setting $\vartheta=\psi$ in the factor $\Phi$, and expanding the argument of the cosine only to first order in $\vartheta-\psi$. The integration over $\vartheta$ can then be performed with adequate precision, leading to

$$hh'|\tau\rangle=(8\pi^2P^2D^2/r)\int\kappa^3\Phi(\omega,\psi)$$

$$\cdot\exp(-\tfrac{1}{2}\kappa^2\eta_r{}^2D^2/r)\cos(\kappa\xi_r-\omega\tau)d\omega, \quad (46)$$

where

$$\begin{aligned}\xi_r&=\xi\cos\psi+\eta\sin\psi,\\ \eta_r&=-\xi\sin\psi+\eta\cos\psi,\end{aligned} \quad (47)$$

are the components of $\boldsymbol{\xi}$ parallel and perpendicular to **r**.

Before attempting to perform the remaining integration, it is convenient to make the change of variable

$$R=g/\omega U;$$

then, after some reductions, Eq. (46) becomes

$$\langle hh'|\tau\rangle=8\pi^{\frac{1}{2}}(P^2D^2/rL)(\mathcal{T}/\mathcal{L})$$

$$\cdot\int B^2\exp(-\tfrac{1}{2}\kappa^2\eta_r{}^2D^2/r^2)\cos(\kappa\xi_r-\omega\tau)dR, \quad (48)$$

where $B$ is obtained from Eq. (27) by replacing $\theta$ by $\psi$, and $\kappa_0$ by $\kappa$. The integral of Eq. (48) remains intractable, however, unless the approximate Eq. (36) is used for $B$. Then since $4(N+2)>1$, it may be evaluated by the method of steepest descent, and the result is

$$\langle hh'|t\rangle=H^2\exp\{-[(2\kappa_1\xi_r-\omega_1\tau)^2/\mu^2$$
$$+\kappa_1{}^2\eta_r{}^2/\nu^2]/4\pi^2\}\cdot\cos(\kappa_1\xi_r-\omega_1\tau), \quad (49)$$

in which the symbols have the meanings explained in the following paragraphs.

The factor $\cos(\kappa_1\xi_r-\omega_1\tau)$ indicates that the waves have the dominant wave number and frequency

$$\kappa_1=g/U^2\cos^2\psi,\quad \omega_1=g/U\cos\psi. \quad (50)$$

Since the surface disturbance has a random character, no unique value of wave number and frequency can be assigned to it; these dominant values correspond roughly to a maximum in the spectrum. The appearance of $\xi_r$ in the cosine factor indicates that the dominant direction of wave travel is radially outward from the center of the storm. Equation (50) shows that the dominant waves depend on the angle $\psi$ which this direction makes with the wind. In particular, the dominant phase velocity is $\omega_1/\kappa_1=U\cos\psi$, which corresponds to the discussion of Sec. 6, and to the observation that, when $\psi$ is small, the phase velocity is nearly equal to the wind velocity. There is no empirical evidence bearing on the dependence of phase velocity on $\psi$.

In the exponential factor of Eq. (49), the quantities $\mu$ and $\nu$ are defined by

$$\begin{aligned}\pi^2\mu^2&=64+(4\mathcal{T}^2/\cos^2\psi),\\ \pi^2\nu^2&=r^2/2D^2.\end{aligned} \quad (51)$$

This factor determines the coherence properties of the wave field. It may conveniently be discussed first for the special case $\xi_r=\eta_r=0$, which corresponds to observations made at one point over the time interval $\tau$. The factor diminishes from 1 to $1/e$ when $\omega_1\tau$ increases from 0 to $2\pi\mu$; $\mu$ is therefore the number of waves in a coherent train. Observationally, this ranges from 5 to 10, corresponding (with $\psi=0$) to $\mathcal{T}=7$ to 15. For $U=20$

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‡ As used here, the word "fetch" has a slightly different meaning han in the current literature on surface waves. It is usually efined as the path over which the wind travels in order to reach he point **r**. Since the usual assumption is that the waves travel only the direction of the wind, the ultimate intents of the two denitions are the same.

meters per second, the corresponding range of $\mathcal{T}$, the life of the gust, is 15 to 30 seconds.

The exponential factor may next be considered for $\eta_r=0$, $\tau=0$ which corresponds to simultaneous measurements (say on an aerial photograph) at two points separated a distance $\xi_r$ in the radial direction. The factor then diminishes to $1/e$ when $2\kappa_1\xi_r=2\pi\mu$ or $\xi_r=\frac{1}{2}\mu$ wavelengths. The factor 2 is readily identified with the ratio of phase and group velocity; because of this, the dominant number of waves in a train, when observed in this manner, should be only 2 to 5. This is confirmed by the fact that aerial photographs generally appear to be even less periodic than are the height-time graphs produced by wave recorders. When $\xi_r=0$, $\tau=0$ the exponential factor determines the crest length of the waves to be $\nu$ wavelengths. If $r=10D$, $\nu=2.2$ in fair agreement with aerial photographs, although no quantitative data are available.

By setting $\xi_r=\eta_r=0$, $\tau=0$ in Eq. (49), it is seen that $H$ is the rms value of $h$; this quantity is defined by

$$H^2=8\pi(P^2D^2/rL)G^2/[1+(16\cos^2\psi/\mathcal{T}^2)]^{\frac{1}{2}}, \tag{52}$$

and

$$G^2=(\mathcal{L}/\cos^2\psi)^3\exp[-(\mathcal{L}/\cos^2\psi)^2] \quad \text{if} \quad \cos\psi>0;$$
$$=0 \quad \text{if} \quad \cos\psi<0. \tag{53}$$

Because of the large value of $\mathcal{T}$, the radical in Eq. (52) may be considered as a correction factor whose value differs only little from unity; except for this factor, $H$ is independent of $\mathcal{T}$, to the approximation here achieved. For constant $\psi$, $H$ varies inversely as $r$, as is required for the conservation of energy. The function $G^2$ has a maximum value $G_m{}^2=0.640$ when $\mathcal{L}/\cos^2\psi=1.225$, and approaches zero for larger and smaller values of this argument. For $\mathcal{L}>1.225$, the value $G_m$ is not attained, but $G$ has its largest value ($<G_m$) when $\psi=0$, and diminishes fairly rapidly with increasing $|\psi|$. For $\mathcal{L}<1.225$, $\psi=0$ is a minimum, and $G$ attains the value $G_m$ for some angle $\psi_m$, dropping rapidly to zero when $|\psi|>\psi_m$. These properties of $G$ reflect those of the function $B$, from which it is derived.

In any actual storm, there will undoubtedly be gusts that have any pre-assigned value of $\mathcal{L}$. From what has just been said it is clear that those for which $\mathcal{L}$ is large ($>3$) will be ineffective in producing waves of any kind. Those gusts for which $\mathcal{L}$ is small ($<\frac{1}{3}$) will cause waves that travel at a large angle to the wind, and have a correspondingly short period. One may therefore conclude that those gusts which cause waves traveling in the general direction of the wind§ have values of $\mathcal{L}$ in the range 0.3 to 3. A typical gust might therefore be characterized by $\mathcal{L}=1$, $U=20$ m/sec, and thus have an actual radius of $L=40$ meters.

By using wave-height data from an actual storm, Eq. (52) may be used to estimate the value of $P$, wh is the rms wind pressure at the center of the ideali storm under consideration here. For this purpose, may take $G=G_m$, and simplify Eq. (52) to the fo

$$H^2=10P^2D^2/rL.$$

(

The weather maps for January 17 and 18, 1945 sho storm at about lat 45° N., long 165° W., with winds o least 46 knots $=24$ m/sec for more than 14 hours. waves due to this storm were recorded[11] at vari points on the west coast of the United States, and average height, reduced to deep water off Morro B California, was $2H=2.8$ m, while the period was 16 s From the maps, $D=425$ km, $r=3800$ km. The value $L$ may be estimated at 58 m, a value obtained fr $U=24$ m/sec and $\mathcal{L}=1$. Eq. (52.1) then yields $P=$ cm. This value may be compared with $\frac{1}{2}\rho_aU^2=3.8$ $\rho_a$ being the density of air.

The writer is indebted to R. S. Arthur for additio data enabling the comparison of this theory with equations used in forecasting storm waves. The p dicted heights of storm waves, when used as above Eq. (52.1), yielded a value of the ratio $P\div\frac{1}{2}\rho_aU^2$ t was nearly unity in the trial case examined.

The question arises, whether fluctuations of t magnitude in the pressure exerted by the wind o horizontal surface are observed. No relevant measu ments appear to have been reported in the literatu but G. C. Ewing and L. N. Liebermann have ea kindly made preliminary measurements of the eff by exposing a water manometer to the action of wind. In general, they agree in setting 0.1 cm as upper limit to the observed pressure fluctuations, though the former noted values of 0.5 cm on one oc sion. These results are not conclusive, but may be tak as an indication of the probable result of more a quately instrumented work.

## 9. THE WAVES INSIDE THE STORM AREA

The explicit calculation of the waves inside the sto area is rendered difficult because of the integration o $\vartheta$ in Eq. (43); outside the storm, this integration made feasible by the special properties of the functi $S(\mathbf{r}\vartheta)$, and led to Eq. (46). At the storm center ($r=$ this function becomes a constant, independent of but this does not make the integration any easi However, in any case the integration over $\omega$ can performed as above, and the expression

$$\langle hh'|\tau\rangle=(4/L)\int_{-\pi/2}^{\pi/2}\{SG^2/[1+(16\cos^2\vartheta/\mathcal{T}^2)]^{\frac{1}{2}}\}$$
$$\cdot\exp[-(2\kappa_1\xi_\vartheta-\omega_1\tau)^2/4\pi^2\mu^2]\cos(\kappa_1\xi_\vartheta-\omega_1\tau)d\vartheta$$

(

is obtained for the correlation of $h$. In Eq. (55),

$$\xi_\vartheta=\xi\cos\vartheta+\eta\sin\vartheta,$$

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§ Present observational practice does not ascribe waves to a distant storm unless their direction of travel is within 30° of the wind in the storm area. It is also known that short period waves are more subject to dissipation than are long period waves, and therefore less likely to travel to great distances.

[11] R. T. Hermanson and R. S. Stump, Tech. Rept. H. E. 1 124, University of California (Berkeley) (unpublished).

and the remaining symbols have the same significance as above, except that $\vartheta$ replaces $\psi$ throughout.

While the quantitative evaluation of this integral is difficult, its physical interpretation is clear. It has been seen that outside the storm area, there is, at each point, a dominantly radial direction of wave-travel; inside the storm, the wave components have not yet separated, and there is no similarly dominant direction. Each point is traversed by waves traveling in many directions; at the center, the only limitation on the sector from which the waves come is the function $G$. If the parameter $\mathcal{L}$ is large, the sector will be relatively narrow, as described above; if $\mathcal{L}$ is small the sector will be wider and, moreover, the period and wavelength will depend strongly on the direction of arrival. At points other than the geometric center of the storm, the function $S(\mathbf{r}\vartheta)$ will also tend to limit the sector from which the waves come, and to cause it to be asymmetric with respect to the wind direction. But, not until the point is well outside the storm area does $S$ narrow the sector into the radial direction as described in the first paragraph of the preceding section.

The Eq. (55) can be used to obtain an estimate of the wave height at the center of the storm; here, from Eq. (45),

$$S=(\pi/2)^{\frac{1}{2}}P^2D$$

and hence

$$H^2=\langle h^2\rangle=4(\pi/2)^{\frac{1}{2}}P^2D\int G^2d\vartheta,$$

provided the radical in Eq. (55) is ignored. The integral can be evaluated graphically; for $\mathcal{L}=1$, its value is about 0.4, so that finally

$$H^2=2P^2D/L \quad \text{at} \quad r=0.$$

Using the data for the storm of January 17 and 18, 1945, we find that $2H=4.2$ m. The highest waves of the storm should be somewhat greater and occur down-wind from the center.

## 10. THE HORIZONTAL COMPONENT OF THE WIND STRESS ON THE SEA SURFACE

Since the sea surface is not everywhere horizontal, and since the wind pressure exerts a force perpendicular to the surface, there will be horizontal forces acting on the water. For simplicity, the mean value of these forces, per unit area of undisturbed surface, will be called the [mean] horizontal [component of the] wind stress—the bracketed words being omitted when no confusion can result. It will be shown that this quantity is not zero in the storm area; it is a horizontal vector, and will be shown to have the same direction as the wind. The unit inward normal to the sea surface has, to a sufficient approximation, the components

$$\partial h/\partial x, \quad \partial h/\partial y, \quad -1;$$

the horizontal wind pressure is therefore

$$\rho g\langle a\nabla h\rangle \text{ dynes/cm}^2. \tag{56}$$

To calculate this, the correlation $\langle ha'|0\rangle$ is first calculated:

$$\langle ha'|0\rangle=\int w(\mathbf{q})\{h_{\mathbf{q}}a_{\mathbf{q}}'|0\}d\mathbf{q}$$

$$=-2(2\pi)^3\Re\int\int\int\int ikA(\mathbf{k}\omega)A^*(\mathbf{k}'\omega)W(\mathbf{k}-\mathbf{k}')$$

$$\cdot\exp\{i[-\sigma(k-\kappa)+\mathbf{k}\cdot\mathbf{x}-\mathbf{k}'\cdot\mathbf{x}']\}d\mathbf{k}d\mathbf{k}'d\omega d\sigma.$$

Proceeding as before, this is seen to be approximately

$$\langle ha'|0\rangle=-2\Re\int\int\int im\Psi(\mathbf{m}\omega)w(\mathbf{r}-\tfrac{1}{2}\sigma\mathbf{m}_1)$$

$$\cdot\exp\{i[-\sigma(m-\kappa)+\mathbf{m}\cdot\xi]\}d\mathbf{m}d\omega d\sigma,$$

so that, neglecting terms in $\nabla w$ as small,

$$\langle a\nabla h\rangle=z\int\int \mathbf{m}m\Psi(\mathbf{m}\omega)K(\mathbf{r},\,\mathbf{m},\,\kappa)d\mathbf{m}d\omega \tag{57}$$

where

$$K(\mathbf{r},\,\mathbf{m},\,\kappa)=\int_0^\infty w(\mathbf{r}-\tfrac{1}{2}\sigma\mathbf{m}_1)\cos[\sigma(m-\kappa)]d\sigma. \tag{58}$$

Now, it follows from the properties of $w$ that $K\rightarrow 0$ for $|m-\kappa|\rightarrow\infty$ and has a sharp peak at $m=\kappa$; therefore, as before, $m$ may be replaced by $\kappa$ everywhere except in $K$. The integration over $m$ can then be performed, approximately, with the aid of the Fourier theorem, resulting in

$$\langle a\nabla h\rangle=2(2\pi)^4w(\mathbf{r})\int\int \mathbf{m}_1\kappa^3\Phi(\omega\vartheta)d\vartheta d\omega. \tag{59}$$

Thus, the horizontal wind stress is at every point proportional to $w(\mathbf{r})=\langle a^2\rangle$, the mean square total wind pressure. The integration over $\omega$, in Eq. (59), can be performed as before, and the result is

$$\langle a(\partial h/\partial x)\rangle=[4w(r)/L]$$

$$\times\int_{-\pi/2}^{\pi/2}\{G^2\cos\vartheta/[1+(16\cos^2\vartheta/\mathcal{T}^2]^{\frac{1}{2}}d\vartheta, \tag{60}$$

$$\langle a(\partial h/\partial y)\rangle=0.$$

The integral in Eq. (60) may be evaluated numerically; for $\mathcal{L}=1$, it is about 0.3. Hence

$$\langle a(\partial h/\partial x)\rangle=1.3w(\mathbf{r})/L;$$

using the same data as before, we find that, at the center of the storm,

$$\rho g\langle a(\partial h/\partial x)\rangle=0.5 \text{ dynes/cm}^2.$$

This may be compared with

$$2.6\times 10^{-3}\rho_a U^2=20 \text{ dynes/cm}^2,$$

which is the accepted value[12] for the tangential stress. The two differ by more than an order of magnitude, so that the horizontal wind stress cannot be called upon to explain those empirical relationships that seem to require the postulate of a tangential stress. Even if one postulates that the actual wind contains many small centers of pressure, that do not contribute appreciably to the formation of long period waves, it is doubtful whether the horizontal wind stress would be increased by a factor of 40.

## 11. CONCLUSIONS

The theory here developed appears to account for a considerable fraction of the observed phenomena, but is unable to account quantitatively for the observed height of the waves. Before speculating about the reason for this, one other phenomenon, which the theory does not clearly explain, should be mentioned.

It is generally believed that there are changes in the spectrum of the waves with position. In the decay area, this is theoretically impossible, except as a result of selective attenuation of the energy in the different frequency regions. However, since, in the present theory the energy is concentrated in a relatively narrow frequency band, it seems very improbable that such an explanation is tenable. Should the existence of a change of wave period in the decay area be established beyond doubt, it would be extremely difficult to construct any theory to account for it.

Inside the storm area, the dependence of the fetch integral, $S(\mathbf{r},\vartheta)$, on position implies a variation of the spectrum of the waves with position. There is thus a general similarity between theory and observation. It is difficult to believe that this is a quantitative identity, however. It is possible that selective attenuation (breaking of shorter waves) must be invoked, or even that the empirical analysis of the data is in error at this point.

Turning now to the basic question of the adequacy of the mechanism assumed for the purposes of this calculation, the value of $P$ required for the generation of surface waves of the observed heights is possibly 10 times greater than the actual value of this quantity.

Moreover, in laboratory experiments,[13] wind waves have been generated under conditions that preclude t possibility of this mechanism. These laboratory wav were highly rotational, as is shown by the stro surface current and shear that were associated wi them. Their major cause was undoubtedly a tangent wind-stress, rather than a normal pressure—not ev a sheltering effect would account for the surfa currents, although such an effect may have been co tributory to the growth of the waves.

The interpretation of such experiments therefo requires the construction of a theory of forced, rot tional waves, which will be considerably different th the one developed above. It is not certain that this also necessary for the interpretation of ocean wav The question is this: is the ratio (tangential stres normal stress) independent of wavelength and the oth parameters that are different in the laboratory than the open? The answer is not obvious, nor are all t relevant parameters known.

It does appear certain that the normal wind pressu is not the only mechanism by which energy is tran ferred from the air to the water. Apart from the ta gential stresses, one other mechanism suggests itse This is the one that is responsible for the well-know Helmholtz instability.[14] While the relation of this effe to observed phenomena is in considerable doubt, an certainly is not simple, the effect itself is scarcely to b questioned. Apart from the question of the quantitati adequacy of Helmholtz's equations, they show that th kinetic energy of the wind can become available to th growing water wave even in the absence of tangenti stresses. This source of energy has not been included the present calculations, but may well be important.

## ACKNOWLEDGMENT

This paper has had the benefit of discussion by number of people. Several erroneous conclusions hav consequently been eliminated, which would not othe wise have been detected; however, the author alone responsible for any that remain. He is especial indebted to R. S. Arthur, G. C. Ewing, L. N. Liebe mann, and W. H. Munk, for ideas and material tha have been included in the text.

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[12] See reference 1, p. 11.

[13] J. W. Johnson and E. K. Rice, Trans. Am. Geophys. Union 33, 845 (1952).

[14] See Reference 4, pp. 109, 373. A summary of later work contained in the article by W. H. Munk, J. Marine Resear (Sears Foundation) 6, 203 (1947).

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# DOLPHIN PROTECTING DEAD YOUNG

On July 12, 1952, while in the observing tower of the San Diego County Life Guard Station at Imperial Beach, California, Life Guard Lieutenant Allan D. Holder observed, in a school of four or five, a dolphin swimming at the surface with some object held astraddle its dorsal fin. The group was moving alongshore about one-fourth mile off the long sandy beach. Perhaps 40 or 50 dolphins were sighted during the day and schools had been seen this year more frequently than usual. The one with the object draped over its fin swam at the surface like a shark, with its dorsal fin almost continuously exposed, but kept up with the others that were rolling out and submerging as usual. In order to make a closer inspection Lieut. Holder and a helper put out in a dory and gradually overtook the group. About four times the object became detached, but each time the dolphin came up under it again and continued with it at the surface. When approached closely the adult submerged and took off. When the dory was brought alongside, the object that had been carried proved to be a young, presumably newborn dolphin about four feet long, so long dead that it was largely disemboweled and quite limp. After moving off about 25 feet and resting at the oars quietly for some time, Holder saw the adult dolphin return and make off again with the dead young hung over its dorsal fin. Two and a half hours later it again passed the life guard station, carrying the young in the same way. Holder feels quite sure that the same individual was performing each time, for its dorsal fin was a little smaller than those of its companions, and it was otherwise distinctive.

Many incidents have been recounted of dolphins showing apparent care and solicitude for dead dolphins and other objects, even human corpses. In the oceanarium of Marineland, Florida, captive adults of the Atlantic bottlenose dolphin, *Tursiops truncatus* Montagu, have shown great solicitude for newborn young, dead as well as alive (McBride, Nat. Hist., 45: 29, 1940; McBride and Kritzler, Jour. Mamm., 32: 254, 1951).

An apparent effort of an adult dolphin to protect a wounded companion has been reported to me by John F. Janssen, Jr., of the California Department of Fish and Game, who kindly permits the publication of his observation. On October 8, 1939, an adult striped dolphin, *Lagenorhynchus obliquidens* Gill, was harpooned from the M. V. "N. B. Scofield" in Bahía Ballenas, Baja California, two miles offshore and 18 miles south of the west end of Holcombe Island. Another adult, thought by Mr. Janssen and party to be the mate, stayed close beside the harpooned individual, frequently forcing its way between the dying beast and the ship and pushing it away. The skull of the harpooned individual is deposited in the Museum of Vertebrate Zoology of the University of California at Berkeley (No. 95088). Photographs presented by Mr. Janssen confirm the identification cited above. *Lagenorhynchus obliquidens* and *Delphinus bairdi* True are the two common dolphins of the open sea off the coasts of California and Baja California.

The solicitous parent that was observed by Lieut. Holder was almost surely a Pacific bottlenos dolphin, *Tursiops gilli* Dall, a species extremely close to the one kept and trained at Marineland, if not identical. He said it was one of the kind that repeatedly courses along Imperial Beach. As I have recently indicated (in the note by Kenyon, Jour. Mamm., 33: 385–387, 1952), *Tursiops gilli* is the dolphin that occurs in the bays and lagoons and along the beaches, in and near the surf, in southern California and along the coasts of Baja California. I have seen thousands in such habitats, and the open-water species almost never penetrate into the inshore habitat of *Tursiops*.

I am indebted to Lieut. Holder not only for this data but also for other information regarding the marine life of his region. I feel full confidence in the accuracy of his observations and reports.—CARL L. HUBBS, *Scripps Institution of Oceanography* (*University of California*), *La Jolla, California. Received September 24, 1952.*

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# API RESEARCH PROJECT 51—STUDY OF NEAR-SHORE RECENT SEDIMENTS AND THEIR ENVIRONMENTS IN THE NORTHERN GULF OF MEXICO

## The First Two Years

Francis P. Shepard* and Clarence L. Moody†

## ABSTRACT

**Two years of full-scale operation of Project 51 have resulted in the establishment of criteria which should prove helpful in recognizing many depositional environments in ancient sediments. As the result of new techniques involving many lines of investigation, it is now possible to distinguish among Texas coast samples at least 14 environments in the embayments, on the barrier islands, and on the open continental shelf. A considerable number of sedimentary units also have been distinguished off the east side of the actively growing portion of the Mississippi delta. The results of this work have a particular application to the finding of ancient shore lines. The work also has indicated the importance of the barrier sand islands as potential stratigraphic sand traps. These elongate islands appear to include the most promising sediments for producing future permeable formations along the Gulf Coast, especially in the Texas area and perhaps also around the Mississippi delta. Available well logs indicate that these masses have considerable thickness, and they apparently are being deposited between contemporaneous fine-grained sediments.**

**Evidence obtained to date indicates that very rapid deposition, at least as much as 2 ft to 3 ft per year, is occurring off the mouths of the large rivers, even where they empty into the open gulf. Appreciable post-glacial deposition has occurred on portions of the open continental shelf, but elsewhere on the Gulf Coast shelf deposition has been slow or non-existent during this interval of about 10,000 to 20,000 years. In the bays of Texas a rate of sedimentation of approximately 3 ft per century is indicated.**

## INTRODUCTION

Perhaps one of the most important functions which a geologist can have in both economic and general scientific research is to define the environments in which various sedimentary formations were deposited. In the past interpretations of marine environments have been based almost entirely on studies of the ancient sediments, either those now exposed on land or those brought to the surface by drilling operations. About 10 years ago members of the Research Committee of the American Association of Petroleum Geologists made a survey of research needs in the field of petroleum exploration and, in the resulting reports, it was stressed that this approach to the problem overlooked the important possibilities of present-day marine environments where first-hand information on sediments and processes could be obtained. Largely as a result of the efforts of these well-known petroleum geologists, Project 51 was initiated, with the definite purpose of studying the Recent marine sediments in the northern Gulf of Mexico. It has often been said that the stratigraphy of the thousands of feet of sedimentary rocks underlying the Gulf Coast gives indications that conditions of deposition over a long period in the past have been comparable to those which exist at present. The opinion has given special impetus to the work of finding out in detail the nature of sediments which are now accumulating along this coast.

The work on the sediments in this area, which has now been in progress for two years, is by no means the first work of geologists with marine sediments. However, it does represent the first time that a coordinated program with a considerable staff of geologists, chemists, and biologists has been aimed at making an exhaustive study of the environments of deposition and the characteristics of modern sediments in an area where it is highly probable that the sediments of today will become the sedimentary rocks of the future. Furthermore, the project is the first on any appreciable scale which has been focused definitely on discovering the environments in which ancient formations were deposited.

Following the suggestions of the project's steering committee, the first 2 areas to be investigated have been, respectively: 1, the lagoonal coast of Texas where muddy bays are largely separated from the open gulf by elongate sand islands; and, 2, the Mississippi delta where huge amounts of sediment are being carried directly into the gulf and where the delta is building forward over the ocean bottom at an amazing rate. Inasmuch as it seemed inadvisable to take on a third area simultaneously with the other two, it has been necessary to postpone active work on one very important environment, viz., an area where future limestones and coral reefs are being developed. However, a small fund from the project has been used to encourage the work at the University of Miami on the lime sediments around southern Florida. It is hoped in this way to provide a satisfactory background for possible future project work on the calcareous environments.

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## Teamwork, New Techniques, and Standardization

In the early stages of the project it was found necessary to develop many new field and laboratory techniques in order to obtain results which could be coordinated and translated directly into characterizing environments. The natural tendency for the specialists in all of the project fields—including clay minerals, organic and inorganic chemistry, macroörganisms, Foraminifera, Ostracoda, pollen, and microbiology—is to derive from the study of a set of samples some statistical measures which are of great interest to their fellow-specialists, but of little apparent relation to a collective undertaking like that of API Project 51. In order to bring each of these studies into the environment picture, it was first necessary to define the environments in terms of such factors as depth and salinity of water, nature of waves and currents, sources of sediment, and general physical character of the sediments. After information on these factors had been obtained, it was then necessary for each of the special study groups to find some means of expressing their statistical results in terms of the various environments. Progress is being made, but a considerable amount of work is still necessary before a satisfactory correlation can come from all of these different lines of work.

The numerous general studies of sediment characteristics made in the past have utilized more or less standard procedures, such as histograms, cumulative curves, and expressions of sorting and skewness. Many of these have proved unsatisfactory when applied to show the fundamental differences among sediments in different environments. To remedy the situation, new parameters have been devised which are more helpful in distinguishing environments. By the use of new methods of plotting the results of the grain-size analyses, by showing graphically the results of estimations of the components of sieve sizes of the coarse fractions of the sediment, and by the utilization of assemblages of Foraminifera, it is now possible to distinguish a large number of the present-day environments along the Gulf Coast. All of the other studies are contributing in varying degrees to the same purpose.

It is somewhat of a handicap to employ nomenclatures which mean different things to different people. Thus some geographic names are used to imply different types of environments in different areas. As an example, along much of the Texas coast the word "pass" is used to represent an entrance into a bay, whereas in the Mississippi delta "pass" means a river distributary channel. "Bayou" is even more ambiguous, as it refers to at least three different types of environments. In order to bring some uniformity into the nomenclature, terms have been suggested which seemed to be the most commonly used for the various features. Sediment names and the boundaries between sediment types have been extremely varied, so that in this respect also an attempt has been made to bring about uniformity. In all this work numerous recognized authorities have been consulted, and the results represent the combined opinions of many people. Above all else, the new ter have been made as simple as possible, and diffic new names which are hard to remember have be avoided.

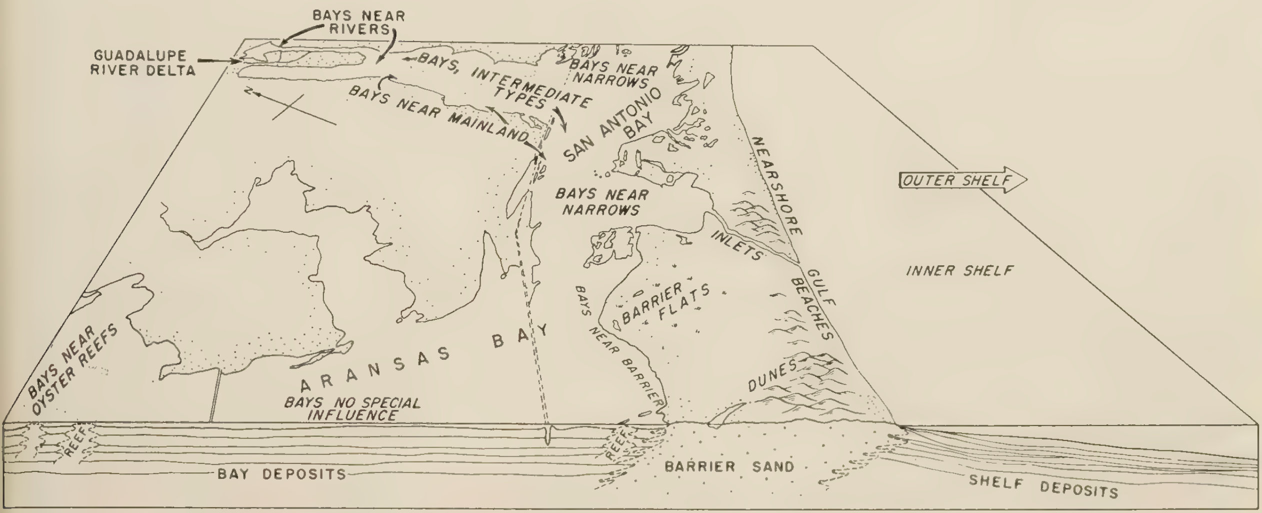
The boat work has included many of the new devi which have been developed in recent years by ocea graphic institutions, such as piston corers, orange-p snappers, bident corers (which take two closely spac cores simultaneously), biplane deflection-current mete and molecular-filter water samplers. Soundings a taken continuously by echo-sounding devices, and t positions of these lines are obtained from numero horizontal sextant angles. New techniques are employ both in sampling and in making chemical field te of freshly collected cores. Special settling-tube a hydrometer methods have been set up for rapid gra size analyses. Much developmental work has been nec sary to perfect both the instruments and the techniqu and also to provide for situations which were somewh different from those which most of the project person had experienced previously.

## The Texas Bay and Barrier-Island Enviro ments

An area around Rockport and Aransas Pass alo the central portion of the Texas coast was chosen b cause of the small scale of industrial activities whi might contaminate the sediments, because of the a cessibility of the area, and because of the availabili of two marine laboratories which could be used as bas for operations and for laboratory space. In this ar a total of approximately 900 samples (mostly cores a few feet in length) has been taken. The analys of these samples have been proceeding at a rate whi is keeping pace with the field work in most respec so that the trend of the project is now clear.

### Description of Environments

By the use of results of general geomorpholog observations, and by the use of more than 100 micr scopic estimations of the composition of coarse-fracti sievings, 14 different environments have been defin (Fig. 1)—7 of them in the bays, 4 within the barri islands, and 3 on the continental shelf of the open Gu of Mexico. These include: bays near mainland; ba near rivers; bays near oyster reefs; bays, intermedia type; bays, no special influence; bays near narrow bays near barriers; barrier flats; inlets; dunes; gu beaches; near-shore gulf; inner shelf; and outer she There is no assurance that all of these environmen are of general application to other similar coastal area nor even to the adjacent portions of Texas. Howev a considerable number of samples has been studied the areas to the north and east of our project are and many of the 14 environments have now been reco nized elsewhere and have been found to have simila if not identical, characteristics to those of the Rockpo area.



This diagram (constructed by Don Sayner) indicates the relation of the bay and shelf deposits to the barrier-island sands. The cross-section is partly hypothetical. The same area (near Rockport) is indicated in Fig. 2 and 4.

**Block Diagram Illustrating the Environments of Sedimentation Along the Texas Coast.**

**FIG. 1**

The bay sediments appear to be influenced by entering streams which carry in large quantities of fine sediments and which greatly reduce the salinity of the water. The salinity is particularly important in its relationship to the faunas and, hence, to the fossils which eventually will be found in this environment. The existence of oyster reefs in the bays sometimes is indicated in the sediment, even at considerable distances from the reefs, by the abundance of oyster-shell fragments.* In the portions of bays which are near inlets or narrows where relatively strong currents exist, or which are near the barrier island where there are overwashes during hurricanes, sand is introduced into the otherwise fine-grained sediments, and various organisms are carried in from the open gulf, causing a mixture of the faunas. In some portions of the bays which lack these special influences, the small amount of sand-sized sediment consists, to a striking extent, of Foraminifera. Nearness to either the mainland or to the barrier islands has a decided influence on bay sediments, principally because the more normal bay sediment is overwhelmed by the sandy material characteristic of the adjacent shore.

On the barrier islands the inner fringes next to the bays are apt to be low swampy areas, partly covered with ponds and channels. The interior of most barrier islands consists of sand dunes derived from the sand beaches. The wind's selective influence, and also the vegetation which grows on or around the dunes, differentiates the dunes from the beach sands on which waves have had a direct influence. A special environment of the barrier islands is provided by the inlet channels which connect the open gulf with the inner bays. Many of these inlets exist only during, or shortly after, a hurricane or other abnormal storm tide, but the hurricanes truncate the growing barrier islands with so many channels, which later become healed, that the deposits in these inlets may be quantitatively very important in the subsequently buried sections of barrier islands.

In the open gulf three different environments have been recognized, although there is no certainty as to whether these environments have sharp boundaries or grade from one to the other. In any case, the deposits near the shores of the gulf are of a definite pattern, and the inner shelf has some characteristics which are different from the outer shelf, with a dividing line at approximately 20 fathoms.

### Methods of Distinguishing Environments

The differences between these various environments of the Texas coast have been most strikingly indicated by the plots of estimates of the constituents of various sieved sizes of the sediments' coarse fractions. The procedure is as follows: The material is first treated with hexametaphosphate (to disaggregate the fines) and wet-sieved to separate out the fine fraction. The coarse fraction is then sieved with a Rotop sieving device. Then the various sievings are examined under a binocular microscope, and estimates are made of the significant constituents. Most samples examined by this method have proved to be more related to their particular environment than to any other. Some of these differences are shown in Fig. 2, in which "pie" diagrams are used to show the total content of shells,

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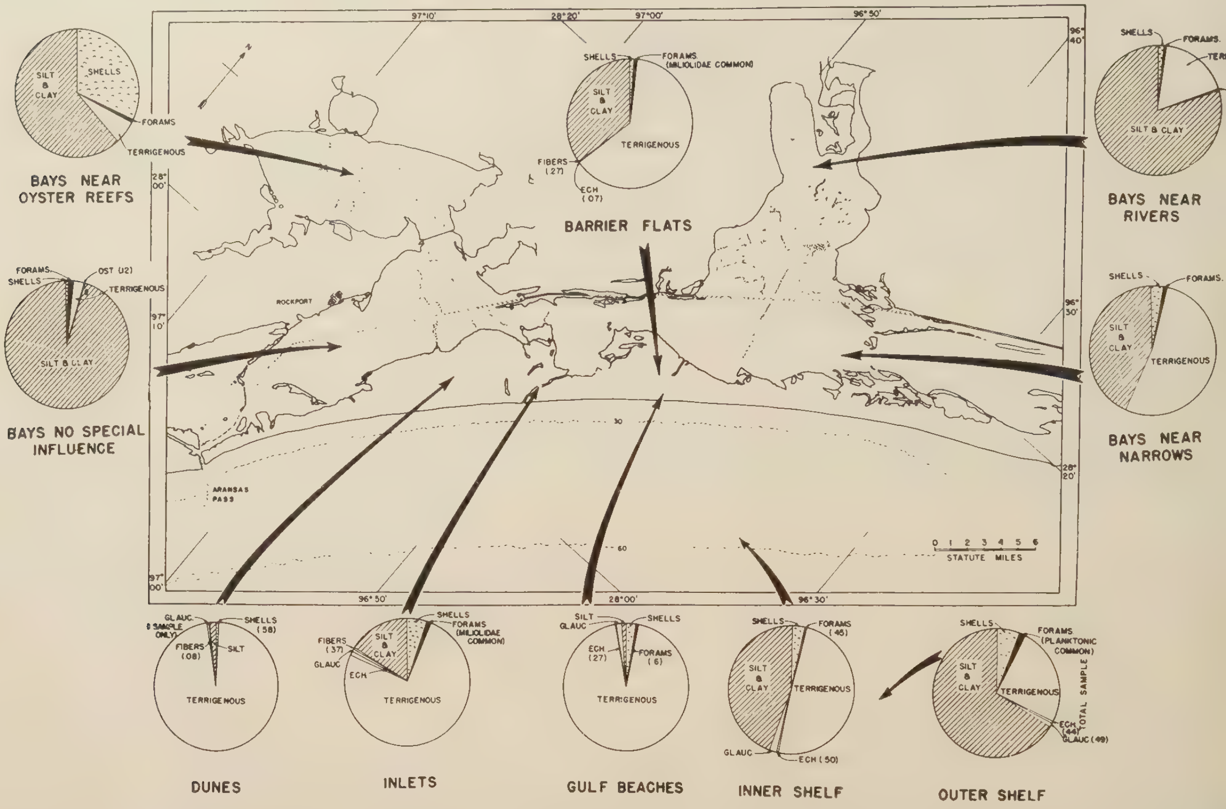
* The possibility exists that commercial oyster-shell dredging has influenced this distribution to an important extent.


SILT & CLAY
SHELLS
FORAMS
TERRIGENOUS
BAYS NEAR OYSTER REEFS
FORAMS
SHELLS
OST (12)
TERRIGENOUS
SILT & CLAY
BAYS NO SPECIAL INFLUENCE
97°10'
28°20'
97°00'
96°50'
SHELLS
FORAMS (MILIOLIDAE COMMON)
SILT & CLAY
TERRIGENOUS
FIBERS (27)
ECH (07)
BARRIER FLATS
SHELLS
FORAMS
SILT & CLAY
BAYS NEAR RIVERS
SHELLS
FORAMS
SILT & CLAY
TERRIGENOUS
BAYS NEAR NARROWS
28° 00'
97° 10'
96° 40'
96° 30'
28° 20'
ROCKPORT
ARANSAS PASS
30
60
0 1 2 3 4 5 6
STATUTE MILES
97° 00'
96°50'
28°00'
96°30'
GLAUC
8 SAMPLE ONLY
SHELLS (58)
FIBERS (08)
SILT
TERRIGENOUS
DUNES
SHELLS
FORAMS (MILIOLIDAE COMMON)
FIBERS (37)
SILT & CLAY
GLAUC
ECH
TERRIGENOUS
INLETS
SILT
GLAUC
SHELLS
ECH (27)
FORAMS (6)
TERRIGENOUS
GULF BEACHES
SHELLS
FORAMS (45)
SILT & CLAY
TERRIGENOUS
GLAUC
ECH (50)
INNER SHELF
SHELLS
FORAMS (PLANKTONIC COMMON)
SILT & CLAY
TERRIGENOUS
TOTAL SAMPLE
ECH (44)
GLAUC (49)
OUTER SHELF

The "pie" diagrams give the ratios of the principal constituents of the coarse fraction to each other and to total quantity of the fine fraction (silt and clay). Note that "terrigenous" refers to the land-derived mineral the coarse fraction, chiefly quartz in this area.

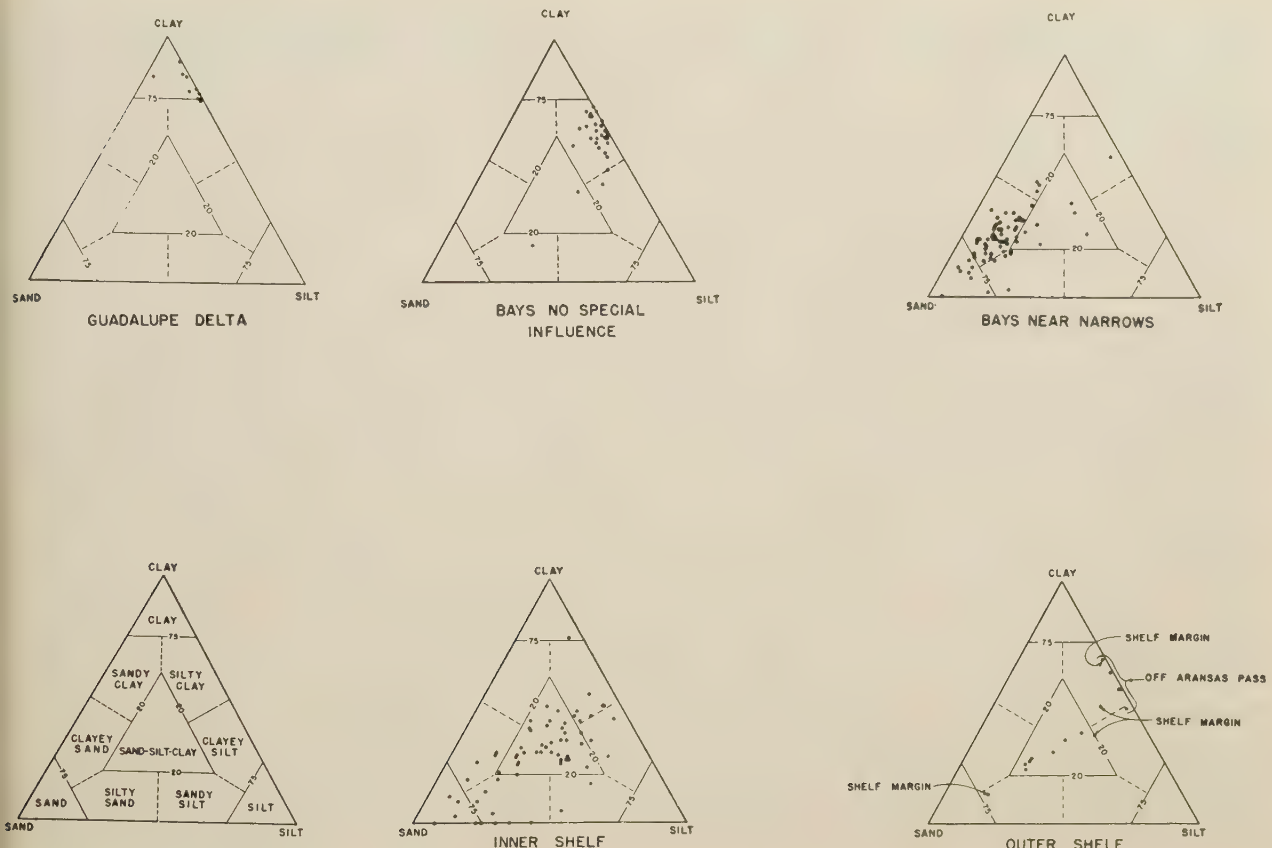
**Types of Sediment Related to the Depositional Environments of the Texas Coast.**

**FIG. 2**

Foraminifera, land-derived sand grains, wood fragments, and other materials in the coarse fraction in comparison with the content of fine sediment. Other more complicated methods are used for these comparisons, but they will not be considered here. Some of the environments can be distinguished by the relationship of sand, silt, and clay in the samples, as indicated in Fig. 3, in which it will be noted that the points are grouped very differently. Other environments are less distinctive in this respect, so that the triangle diagram is not applicable.

The general assemblages of Foraminifera are quite distinctive in some of these Texas coast environments. This is illustrated by Fig. 4, in which pictures are included of a typical assemblage of Foraminifera from a bay near a river mouth, from an unmixed bay, from the swamps on the inner side of the barrier islands, and from the open shelf. It will be noted that each of these environments is the equivalent, approximately, of one of the 14 environments developed through the microscopic studies of the coarse fraction. The macroörganisms, such as mollusks, corals, and echinoids, are influenced by the environments in somewhat the same ways as are the Foraminifera. The ostracods of salinity environments are quite distinct from thos high-salinity. Pollen is wind-transported and, he is influenced by such factors as the distance from and the abundance of pollen-producing plants on land. Thus the sediments on the low flats inside barrier islands appear to have the largest amount pollen in the Rockport area.

The clay minerals have been found by Universit Illinois clay specialists to vary in their relations according to whether they were deposited in fr brackish, or normal marine water. This is showr a relationship between montmorillonite and illite between montmorillonite and chlorite, with the hi ratios representing the lower salinities. Similarly, chemists are finding that there may be variation the chlorinity of the interstitial water in some ments, depending on the salinity at the time of d sition. This can only be a relative difference, bec post-depositional water migration in the sediments r change the original salinity. Also the carbon and trogen, at least, in Recent sediments vary accor to environments. Spectrochemical analyses made



GUADALUPE DELTA

BAYS NO SPECIAL INFLUENCE

BAYS NEAR NARROWS

INNER SHELF

OUTER SHELF

These ratios are expressed in triangle diagrams. The lower-left triangle gives the sediment names adopted by he project.

**Ratios of Sand, Silt, and Clay in Some of the Texas Coast Environments.**

**FIG. 3**

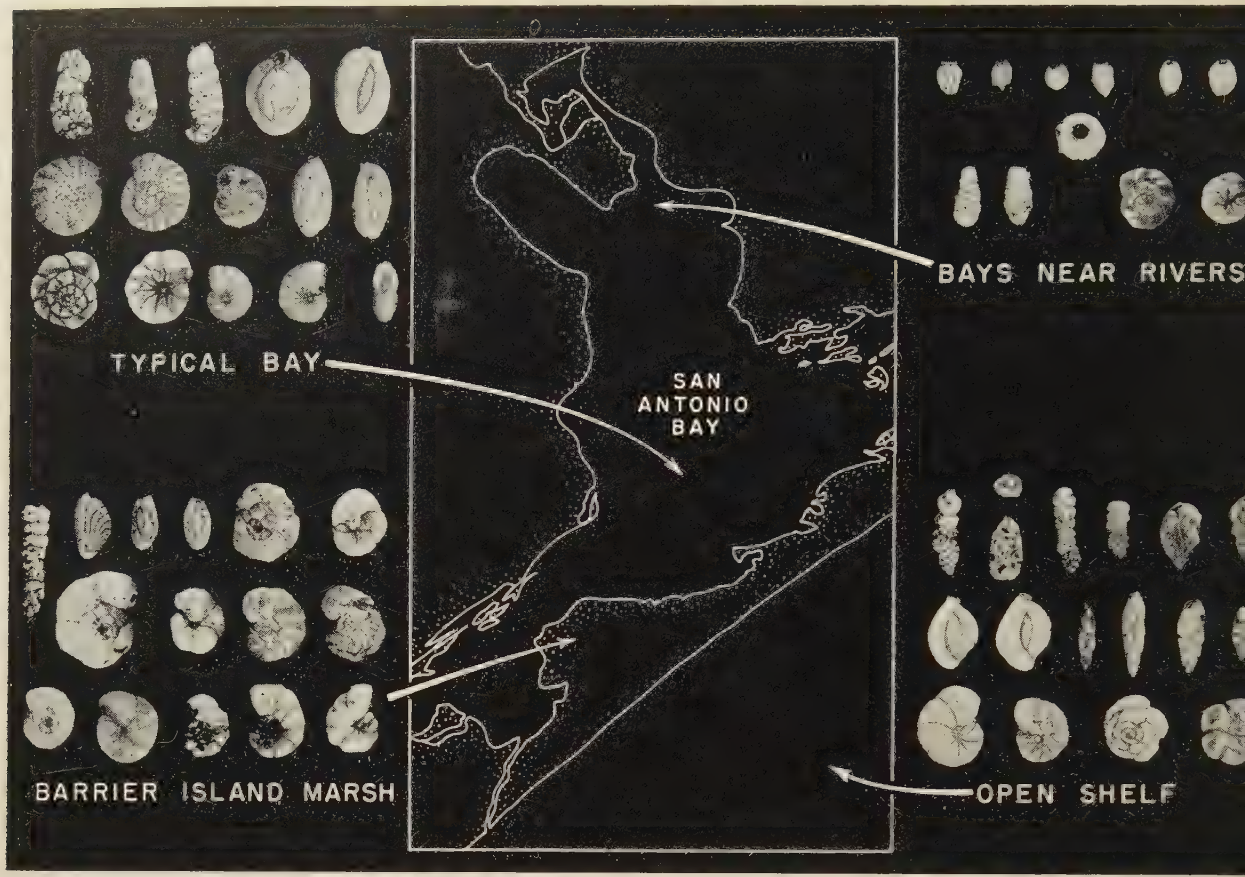
---

he project by California Research Corporation indicate hat the $\frac{Al_2O_3}{K_2O}$ and $\frac{Al_2O_3}{Na_2O}$ ratios decrease with distance rom the Guadalupe delta.

### Test of Environment Studies

The preceding discussion illustrates how the various tudies are accomplishing the purpose of the project n the development of methods of distinguishing between he various depositional environments. The project has ow proceeded far enough so that tests can be applied t least to the Recent sediments of the central Texas oast with a considerable certainty that their environments can be ascertained. As evidence, 10 scattered amples from the Rockport area and adjacent portions f the Texas coast were examined, with locations temorarily withheld. Of these it was possible to pick he exact environment in nine cases by the coarse-raction method alone, and the tenth environment was asily recognized by the Foraminifera. Various other ests were helpful in confirming most of these environments. Such a good record cannot be anticipated in all cases because some samples are gradational between two environments, and others no doubt have had some unusual influence which may make their appearance deceptive. Nevertheless, the record looks promising at the present time, and more opportunity to check the methods is being awaited.

The tests on Recent surface samples do not necessarily indicate that the methods can be applied to older formations now deeply buried; and, no doubt, some modifications to the criteria must be applied for older formations even where similar environments of deposition existed. To date, members of the project have tested certain samples obtained in test holes extending down to approximately 40 ft along portions of the Texas coast. In these samples certain characteristics were found which indicate that the environments can be recognized quite readily, even after shallow burial has occurred. Deeper burial will no doubt cause modifications, and it will be more difficult to disaggregate the formations for examination of the coarse fractions



**Foraminifera Assemblage Characteristic of Four Texas Coast Environments. (Data supplied by Frances L. Park**

**FIG. 4**

of the sediment without the elimination of some of the important elements of these fractions. However, it seems likely that there will remain sufficient characteristics to determine the following environments: 1, open-shelf deposits, with distinctions between those formed near shore and those on the outer shelf; 2, the sand and marsh portions of barrier islands; 3, lower-bay deposits; and, 4, upper-bay deposits near river mouths. The importance of the oil industry's being able to distinguish between the muddy bay sediments and the muddy open-shelf sediments can be seen when it is recalled that between them lie the broad sandy barrier islands which constitute possible future oil traps.

**Continuation of Formation Types in Depth**

The project is currently conducting some coring operations extending to 40 ft or 50 ft in the Rockport area in order to obtain more information on the third-dimensional aspects of present-day types of sedimentation. In the meantime there are some indications that both the sands of the barrier islands and the muddy sediments of the bays do extend down to signific depths. The test holes made in the bays by the a engineers indicate that the sediments alternate betw coarse and fine material, but are of the same gen type down to depths of at least 20 ft or 30 ft. examination of a few samples from borings on barrier islands, obtained by the army engineers anc petroleum companies, has indicated that the sands tinue at least to depths of 30 ft or 40 ft without m indication of change from present-day conditions. sand ridges on the outside of the barrier islands sug some seaward growth which may indicate that sand masses are somewhat displaced in depth. displacement is shown in the speculative subsur interpretation in Fig. 1. However, other evidence sh that some barrier islands are being moved landw under the wave attack of storm conditions which be more important than the accretion which ta place during small-wave conditions. In any case subsidence is faster than upgrowth, there is an portunity for a thick barrier-island sand to bec buried by fine-grained sediments and to be preser as a lenticular or "shoestring" sand body. The gre compaction of the muddy sediments on either side may be expected to produce dips away from the sands.

## The Encroaching Mississippi Delta Environment

Through the efforts of R. J. Russell, H. N. Fisk, and others, much information has become available concerning the Mississippi delta. From the point of view of marine sedimentation, the Recent sediments now being formed peripheral to the delta remained to be investigated. Following the suggestions of the steering committee, the project embarked on an intensive study of the area bordering the east side of the bird-foot delta of the Mississippi (Fig. 5), where rapid advances of the land margin are taking place under essentially natural conditions. In this work very little attention has been paid to the better-known distributaries, South Pass and Southwest Pass, because these have been modified by man for about 100 years. The area bordering Pass à Loutre, Main Pass, and Baptiste Collette subdelta is especially important to stratigraphy because it represents an environment where sediments are accumulating in an open sea at a very rapid rate, in contrast to the Texas area. Very different diagenetic changes may occur because of the rapid burial of these sediments. This area is important also because a source of sand sediment derived from the sea floor, and to some extent from the sand islands to the northeast, is competing with the far greater source of sediment coming from the river mouths. In some places the sediment appears to be a combination of these two sources.

### Comparison of Old and Recent Surveys

Records of the Mississippi delta growth extend back to the 17th century, but the first moderately reliable charts were made in 1838. The U.S. Coast and Geodetic Survey has shown some interesting comparisons of the shore lines of that time with those of 1934. The work of the project, by utilization of recent air-photo compilations, has extended this comparison up to 1952-53. Also we have introduced the third dimension by compilation of maps showing changes in depth which have resulted both from the advance of the subaerial delta and from marine sedimentation beyond the delta margin (Fig. 6). Almost the entire east side of the lower Mississippi delta has been built between 1860 (a year of a better survey than that of 1838) and 1952. This map of the inshore region shows that the greatest vertical change is off Pass à Loutre where the depth is now more than 100 ft shoaler than it was less than a century ago. Actually the bulk of the large changes occurs in a few years directly off the mouth of the advancing distributaries. Fig. 7 shows, in vertical section, the amount of depth change between 1860 and 1952 and the character of the sediment. The sections indicate that, even 4 miles from land, more than 40 ft of fill has been deposited since 1860.

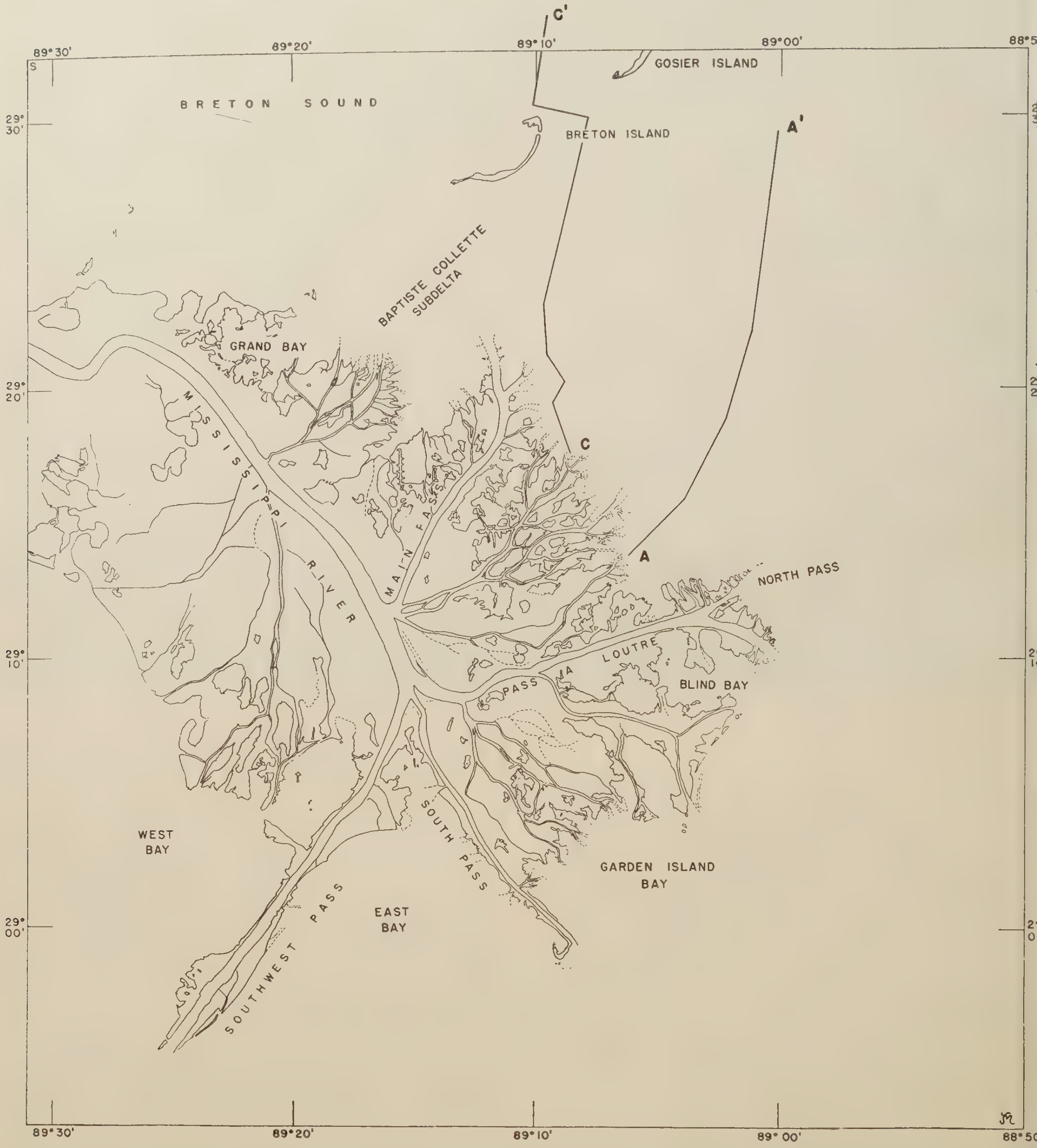
### Overlapping Sedimentary Units Marginal to the Delta

The 562 bottom samples, mostly cores, obtained during the 3 delta field seasons are developing a picture of an encroaching series of sediment types which advance seaward with the advance of the delta (shown in part in Fig. 9). The muddy sediments of the marsh surfaces of the delta, which also include some fine sandy zones in the natural levees along the margins of the stream channels, are bordered and underlain by coarse silts with little sand and considerable wood. This silt generally extends down to depths of from 3 ft to 6 ft, whereas off the major distributaries sand mixed with clay and silt extends to depths of as much as 25 ft to 30 ft. Finer grained sediments occur at shallow depths in some of the interlobes between the delta bulges. Sediments which consist of soft, somewhat laminated, olive-gray silt and clay, with only a small amount of sand and with relatively large quantities of wood, border the silts. These "pro-delta silty clays" are much more extensive than the silts, and they form a band varying from 1 mile to 8 miles wide and extend to depths of approximately 120 ft. Seaward of the "pro-delta silty clays," off the larger distributaries, there is a zone of lighter olive-gray clay which contains a high percentage of Foraminifera and other marine organisms, which lacks lamination, and which is comparatively stiff in contrast to the more fluid sediments nearer the delta.

Outside the "pro-delta silty clays," to the northeast, the sediment consists either of clean, well-sorted sands called "multicycle sands" or of a mixture between the sands and the sediments of the "pro-delta silty clays." To the north, in Breton Sound, there are heterogeneous deposits of buff to dark gray, poorly sorted mixtures of sand, silt, and clay. In contrast to the deposits directly off the active delta to the south, shells are quite common in this area, and these often are concentrated in bands.

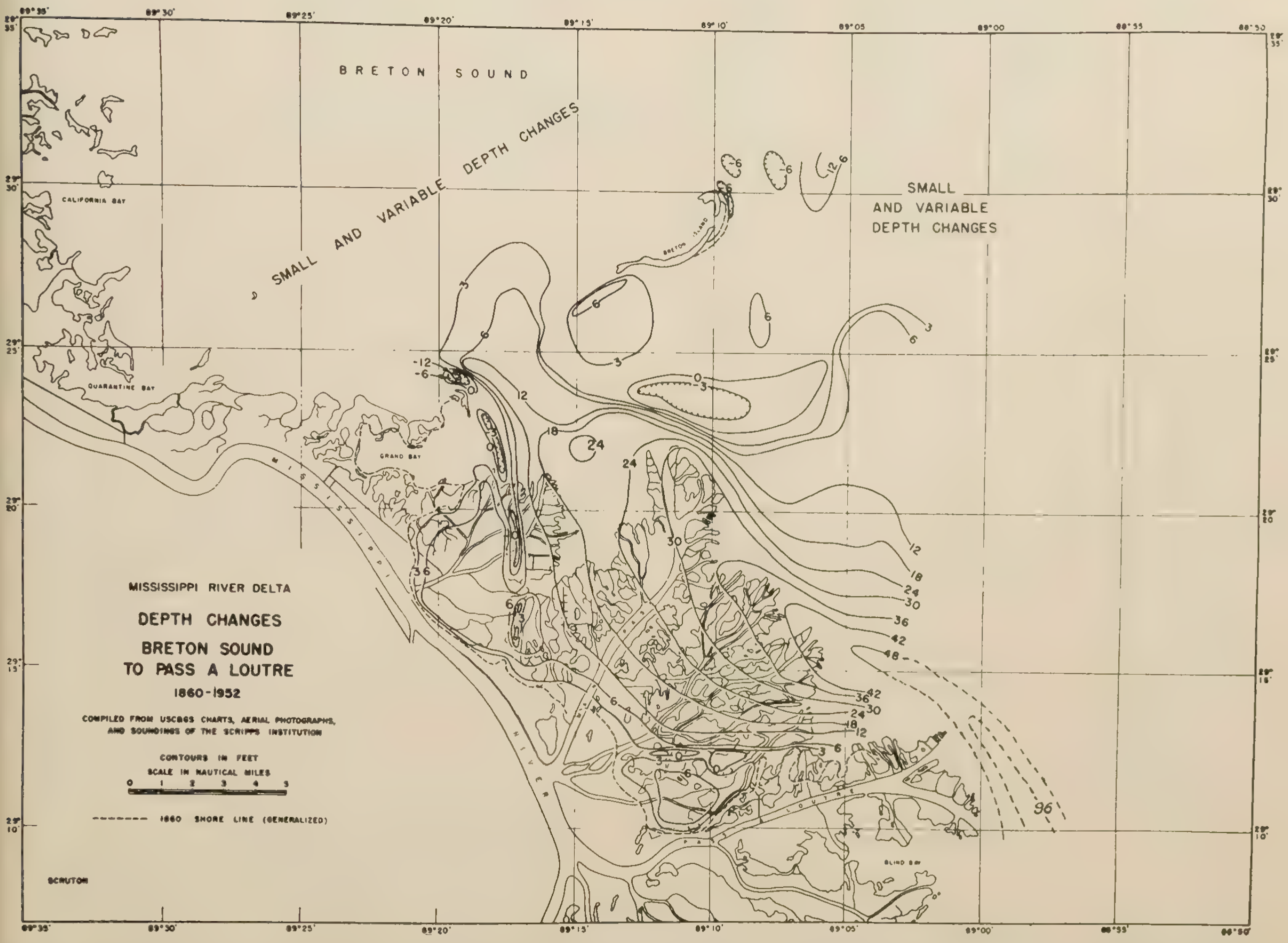
Some of the cores penetrate through the upper layers of the encroaching pro-delta formations and reveal the presence of an outer band of delta sediment, now covered as a result of delta growth (Fig. 6).

The delta sediment zones are of special importance because they indicate that it may be possible to find the direction of the shore line around the ancient delta deposits from the nature of the sediment. Among those features which are indicative of the nearness of a delta and the fast rate of sedimentation can be included: 1, the high clay content throughout a relatively thick homogeneous section, which is unusual on the shelf; 2, the presence of laminations and undisturbed bedding, which also is rare in other marine sediments; 3, the abundance of wood fragments; and, 4, the general absence of glauconite except a considerable distance from the distributaries. Some of these same characteristics have been found on the shelf off the Brazos River of Texas and off Sabine Pass. There seems to be little difficulty in distinguishing the sediments in Breton Sound from those in the open gulf to the south. The faunas of the sediments in the sound are very


C'
89°30'
89°20'
89°10'
89°00'
GOSIER ISLAND
BRETON SOUND
BRETON ISLAND
A'
29° 30'
BAPTISTE COLLETTE SUBDELTA
GRAND BAY
MISSISSIPPI RIVER
MAIN PASS
29° 20'
C
A
NORTH PASS
PASS A LOUTRE
BLIND BAY
29° 10'
WEST BAY
SOUTH PASS
GARDEN ISLAND BAY
EAST BAY
SOUTHWEST PASS
29° 00'
89°30'
89°20'
89°10'
89°00'

**Present Outline of the Mississippi Delta Based on Recent Air Photos; the Two Lines Refer to Sections in Fig. 7.**

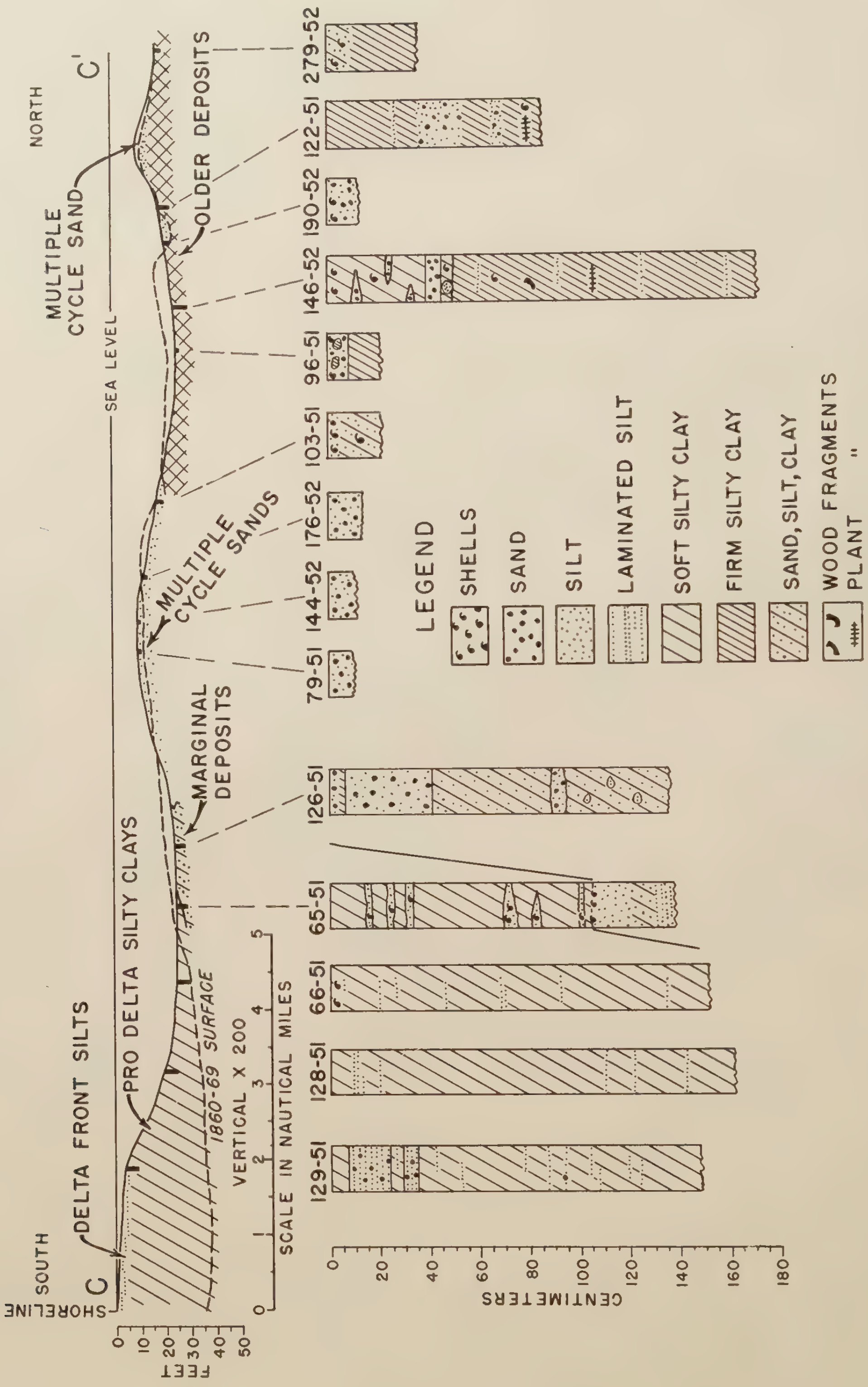
**FIG. 5**


BRETON SOUND
SMALL AND VARIABLE DEPTH CHANGES
SMALL AND VARIABLE DEPTH CHANGES
CALIFORNIA BAY
QUARANTINE BAY
GRAND BAY
BRETON ISLAND
MISSISSIPPI RIVER
PASS A LOUTRE
BLIND BAY
MISSISSIPPI RIVER DELTA
DEPTH CHANGES
BRETON SOUND
TO PASS A LOUTRE
1860-1952
COMPILED FROM USC&GS CHARTS, AERIAL PHOTOGRAPHS, AND SOUNDINGS OF THE SCRIPPS INSTITUTION
CONTOURS IN FEET
SCALE IN NAUTICAL MILES
0 1 2 3 4 5
1860 SHORE LINE (GENERALIZED)
SCRUTON
-12
-6
-6
0
3
6
12
18
24
30
36
42
48
96
89°35'
89°30'
89°25'
89°20'
89°15'
89°10'
89°05'
89°00'
88°55'
88°50'
29° 35'
29° 30'
29° 25'
29° 20'
29° 15'
29° 10'

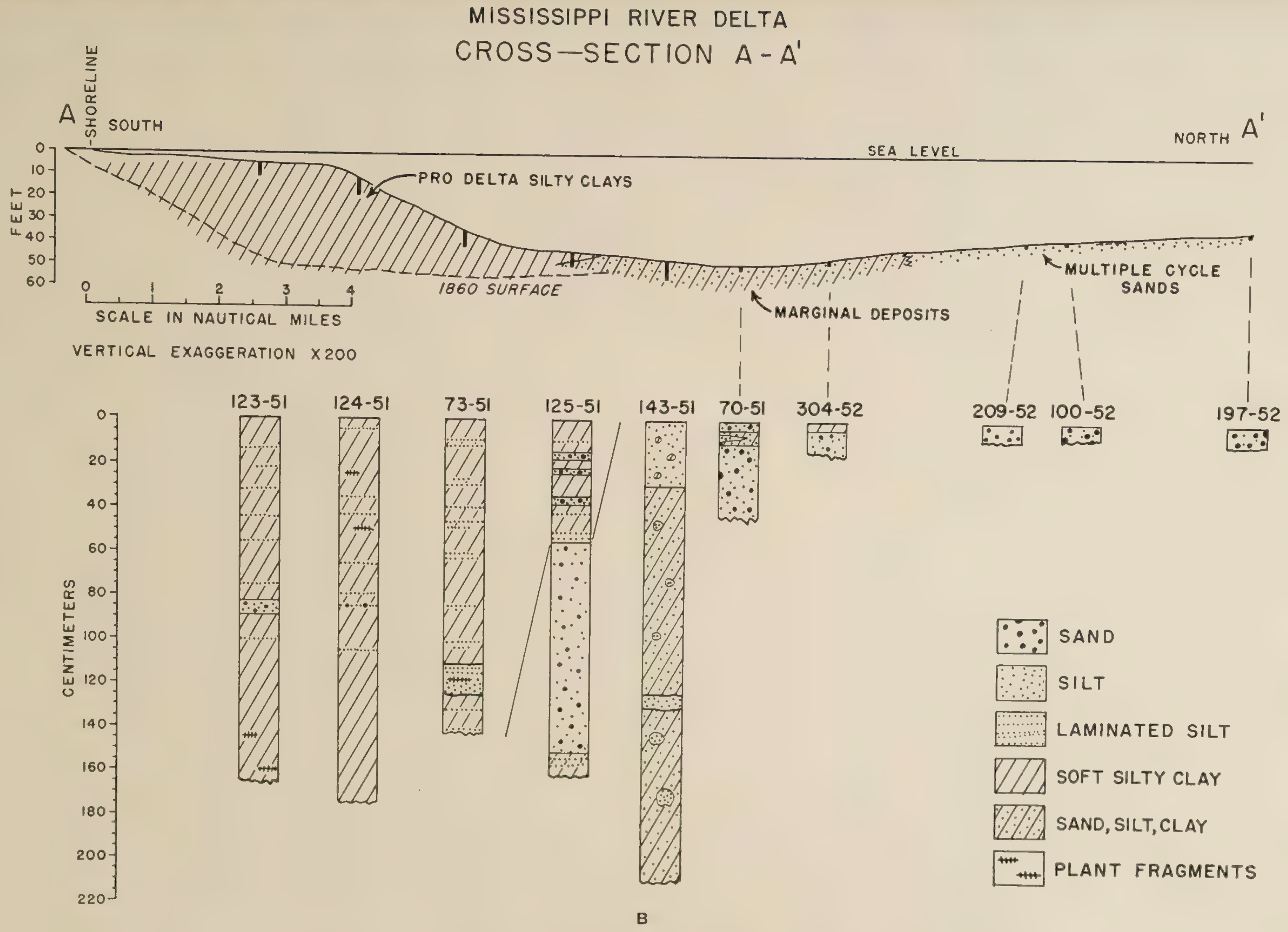
This shoaling resulted from advances of the east portion of the Mississippi delta between 1860 and 1952. The isolines are based on old charts of the U.S. Coast and Geodetic Survey and on recent information obtained in part by the project. (Data supplied by P. C. Scruton.)

**Isolines of Shoaling.**

**FIG. 6**


MISSISSIPPI RIVER DELTA
CROSS—SECTION C - C'
SOUTH
NORTH
C
C'
SHORELINE
SEA LEVEL
DELTA FRONT SILTS
PRO DELTA SILTY CLAYS
1860-69 SURFACE
MARGINAL DEPOSITS
MULTIPLE CYCLE SANDS
OLDER DEPOSITS
MULTIPLE CYCLE SAND
FEET
0
10
20
30
40
50
VERTICAL X 200
SCALE IN NAUTICAL MILES
0
1
2
3
4
5
129-51
128-51
66-51
65-51
126-51
79-51
144-52
176-52
103-51
96-51
146-52
190-52
122-51
279-52
CENTIMETERS
0
20
40
60
80
100
120
140
160
180
LEGEND
SHELLS
SAND
SILT
LAMINATED SILT
SOFT SILTY CLAY
FIRM SILTY CLAY
SAND, SILT, CLAY
WOOD FRAGMENTS
PLANT "

A


MISSISSIPPI RIVER DELTA
CROSS—SECTION A-A'
A
SHORELINE
SOUTH
NORTH A'
SEA LEVEL
FEET
0
10
20
30
40
50
60
PRO DELTA SILTY CLAYS
1860 SURFACE
MARGINAL DEPOSITS
MULTIPLE CYCLE SANDS
0 1 2 3 4
SCALE IN NAUTICAL MILES
VERTICAL EXAGGERATION X200
CENTIMETERS
0
20
40
60
80
100
120
140
160
180
200
220
123-51
124-51
73-51
125-51
143-51
70-51
304-52
209-52
100-52
197-52
B
SAND
SILT
LAMINATED SILT
SOFT SILTY CLAY
SAND, SILT, CLAY
PLANT FRAGMENTS

These cross-sections illustrate the overlapping formations which are developing as the delta front advances. (See also Fig. 9.) (Data supplied by P. C. Scruton.)

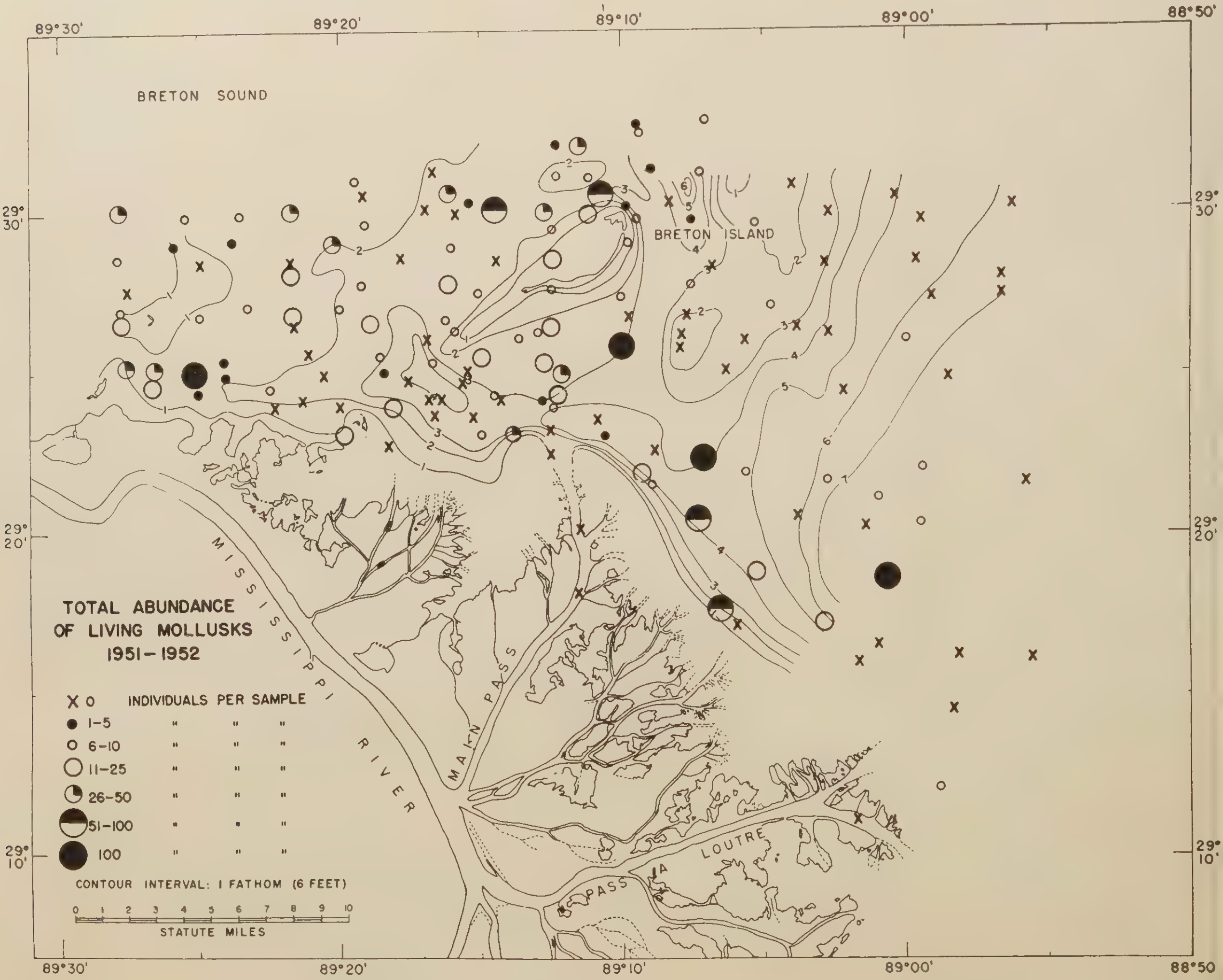
**Cross-Sections Showing Lines of Cores Obtained Transverse to the Delta.**

FIG. 7

different from those in the open gulf, and the sediments have considerably less wood because of greater distance from the distributaries of the Mississippi. Some spectrochemical analyses of samples in and around the delta indicate that differences may exist between different localities. Environment relationships can also be seen on a map which shows the total abundance of living mollusks in the Mississippi delta area (Fig. 8).

### Barrier Islands and Delta Encroachment

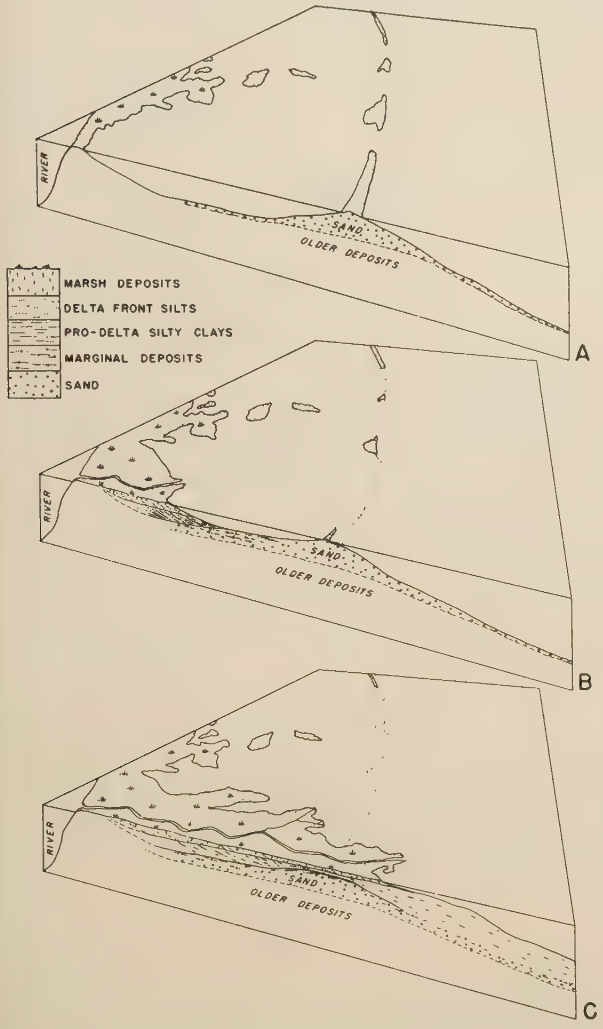
The changes in the barrier islands northeast of the bird-foot delta provide interesting information concerning these sand bodies. The northern Chandeleurs have retreated westward about one-quarter mile in the past century. On the other hand, Gosier Island to the south has had a very significant growth in recent years. The source of sand for this growth must have come from the relatively deep shelf and from the northern Chandeleur Islands. This island was only 0.3 mile long in 1922, and it now exceeds 4 miles in length. In contrast, a chain of barrier islands, which formerly existed to the north of Baptiste Collette subdelta, has virtually disappeared (Fig. 9). It seems likely that these islands have been eliminated because a source of sand which existed up to recent times in the strait inside Breton Island has been covered with fine sediment which began to be introduced to this area in large volume when Main Pass was created. Because this burial eliminates the sand necessary for the maintenance and growth of the islands, they have now retreated, having been largely truncated by waves. Fig. 9


89°30'
89°20'
89°10'
89°00'
88°50'
29° 30'
29° 20'
29° 10'
BRETON SOUND
BRETON ISLAND
MISSISSIPPI RIVER
MAIN PASS
PASS A LOUTRE
TOTAL ABUNDANCE OF LIVING MOLLUSKS 1951–1952
X 0 INDIVIDUALS PER SAMPLE
● 1-5
○ 6-10
○ 11-25
26-50
51-100
● 100
CONTOUR INTERVAL: 1 FATHOM (6 FEET)
0 1 2 3 4 5 6 7 8 9 10
STATUTE MILES
1
2
3
4
5
6

Note sparsity of the fauna in and near the distributary mouths and in the sand area offshore. (Data supplied by R. H. Parker.)

**The Abundance of Mollusks at Various Stations Along the East Side of the Mississippi Delta.**

**FIG. 8**



These sand bodies formerly existed where Baptiste Collette subdelta has been built into the shallow sea. The destruction of the islands apparently is related to the flood of muddy sediment carried into the off-lying area by the rapidly advancing Main Pass to the south. This advance removed the chief source of sand for the feeding of the barrier islands, and it allowed the waves and currents to truncate them. This diagram is based on old surveys and on cores obtained in the area, and it is partly hypothetical. (Diagram constructed by Don Sayner.)

**Block Diagrams Showing the Sequence of Events in the Truncating and Overlapping of Barrier-Island Sand Bodies.**

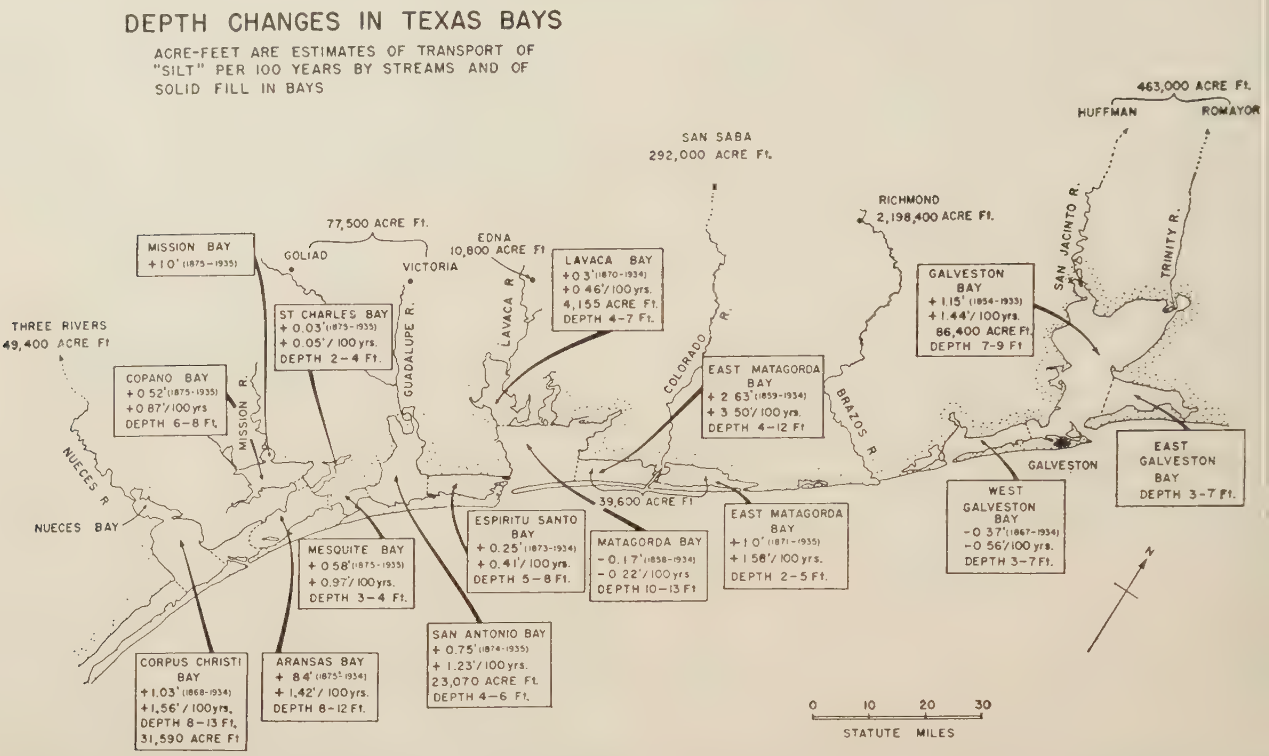
FIG. 9

based on project cores and on charts dated from 1838 to 1952, shows the growth of the Baptiste Collette subdelta, the retreat and final truncation of the island chain, and its subsequent burial. The nature of the sediments associated with these events also is indicated. Such disappearance of sand islands can leave a submerged sand body of considerable thickness. Some of the wells in the barrier island outside Mississippi Sound have penetrated sand to depths of 250 ft. The growth of the muddy sediments of a delta over the eroded top of one of these elongate sand masses may develop a satisfactory stratigraphic trap for future oil accumulation. Similarly, the eastward march of the delta is causing fine sediments to overlap on the older sands of the continental shelf and, hence, may develop other potential stratigraphic traps in the future.

## Rates of Sedimentation Along the Gulf Coast

In the past marine geologists learned far more about rates of sedimentation on the deep ocean floor than on the shallow shelves around the continents. Most of the shelf areas studied in earlier operations have apparently had little or no deposition in the past 10,000 to 20,000 years, i.e., since the melting of the ice sheets caused a general rise of sea level. The finding of glacial-age sediments on the shelves led some authorities to the belief that shelves, in general, are not areas of deposition except very near the shore. However, our studies along the Gulf Coast show definitely that post-glacial deposition is progressing at appreciable rates in many places on the open shelf. The very rapid shoaling during the past century on the shelf outside the Mississippi delta, mentioned previously, provides the best evidence, although this is in a very special environment because of the great size of the river. A line of cores taken off Aransas Pass, Texas, out to the edge of the shelf suggests the existence of modern sediments because of the great uniformity of the silty clays which extend the entire length of 7-ft to 9-ft cores taken beyond the 20-fathom line. If the sea had retreated during a glacial stage, there should be sand layers; or at least the clayey sediments deposited prior to lowering of the sea level would show greater compaction than subsequent sediments. The faunas indicate that these sediments have been accumulating at approximately the same depths as those which now exist, and this fact also suggests that they are post-glacial. However, along other portions of the continental shelves, sands indicative of shallow-water conditions, or even barrier islands, are found. The associated faunas confirm the change of conditions since the time when these coarse sediments were deposited. Accordingly, we are finding that the shelves are, at least locally, sites of deposition which may yield future sedimentary rocks, but that elsewhere conditions of non-deposition exist on the sea floor.

The rate of sedimentation, or at least of bay fill, is particularly well-known along the Texas coast because of the completeness of old surveys and because of the relative ease of comparing the soundings taken as long ago as 100 years with those depths now existing. By the overlay of new charts upon old ones, on a tracing table, thousands of depth comparisons have been made. The results have been translated into contour maps which show the amount of depth change between old and new surveys. A summary of the results is given in Fig. 10. It will be seen that the bays have been


DEPTH CHANGES IN TEXAS BAYS
ACRE-FEET ARE ESTIMATES OF TRANSPORT OF "SILT" PER 100 YEARS BY STREAMS AND OF SOLID FILL IN BAYS
463,000 ACRE Ft.
HUFFMAN
ROMAYOR
SAN SABA
292,000 ACRE Ft.
RICHMOND
2,198,400 ACRE Ft.
77,500 ACRE Ft.
GOLIAD
VICTORIA
EDNA
10,800 ACRE Ft
MISSION BAY
+1.0' (1875–1935)
LAVACA BAY
+0.3' (1870-1934)
+0.46'/100 yrs.
4,155 ACRE Ft.
DEPTH 4-7 Ft.
ST CHARLES BAY
+0.03' (1875-1935)
+0.05'/100 yrs.
DEPTH 2-4 Ft.
THREE RIVERS
49,400 ACRE Ft
COPANO BAY
+0.52' (1875-1935)
+0.87'/100 yrs
DEPTH 6-8 Ft.
MISSION R.
GUADALUPE R.
LAVACA R.
COLORADO R.
BRAZOS R.
SAN JACINTO R.
TRINITY R.
NUECES R.
GALVESTON BAY
+1.15' (1854-1933)
+1.44'/100 yrs.
86,400 ACRE Ft.
DEPTH 7-9 Ft
EAST MATAGORDA BAY
+2.63' (1859-1934)
+3.50'/100 yrs.
DEPTH 4-12 Ft
GALVESTON
EAST GALVESTON BAY
DEPTH 3-7 Ft.
NUECES BAY
39,600 ACRE Ft
ESPIRITU SANTO BAY
+0.25' (1873-1934)
+0.41'/100 yrs.
DEPTH 5-8 Ft.
MATAGORDA BAY
-0.17' (1858-1934)
-0.22'/100 yrs
DEPTH 10-13 Ft
EAST MATAGORDA BAY
+1.0' (1871-1935)
+1.58'/100 yrs.
DEPTH 2-5 Ft.
WEST GALVESTON BAY
-0.37' (1867-1934)
-0.56'/100 yrs.
DEPTH 3-7 Ft.
MESQUITE BAY
+0.58' (1875-1935)
+0.97'/100 yrs.
DEPTH 3-4 Ft.
N
SAN ANTONIO BAY
+0.75' (1874-1935)
+1.23'/100 yrs.
23,070 ACRE Ft.
DEPTH 4-6 Ft.
CORPUS CHRISTI BAY
+1.03' (1868-1934)
+1.56'/100 yrs.
DEPTH 8-13 Ft.
31,590 ACRE Ft
ARANSAS BAY
+.84' (1875-1934)
+1.42'/100 yrs.
DEPTH 8-12 Ft.
0 10 20 30
STATUTE MILES

The boxes contain: 1, the shoaling (+) or deepening (−) in feet since early surveys; 2, the shoaling rate per century; 3, the approximate number of acre-feet of solid sediment per century represented by this shoaling; and, 4, the depth of the main portions of the bay in feet. The acre-feet given in brackets for the rivers represent 100 years at the present rates which are based on U.S. Department of Agriculture and Texas surveys.

**Depth Changes in Texas Bays.**

**FIG. 10**

filling so rapidly that they may cease to exist in a few hundred years. The general fill is supplemented locally by very rapid encroachment onto the bays as the result of delta-building of the larger rivers. However, there are strong indications that subsidence is taking place at the same time, so that an increase in the rate of this subsidence may reverse the trend in the bays some time in the future and may even cause the bays to increase in depth and area. Taking into account a probable present-day rate of subsidence, it is estimated that the average rate of sedimentation in the Texas bays is close to 3 ft per century.

## REFERENCES

### Published Papers

1. R. M. Norris, "Buried Oyster Reefs in Some Texas Bays," *J. Paleontology* **27** **[4]** 569-76 (1953).

2. Frances L. Parker, Fred B Phleger, and Jean F. Peirson, "Ecology of Foraminifera from San Antonio Bay and Environs, Southwest Texas," *Cushman Foundation for Foraminiferal Research, Spec. Publ. No. 2*, 1-75, Jan. (1953).

3. E. L. Puffer and W. K. Emerson, "The Molluscan Community of the South Texas Oyster Reef Biotope," *J. Paleontology* **27** **[4]** 537-44 (1953).

4. P. C. Scruton and D. G. Moore, "Distribution of Surface Turbidity Off the Mississippi Delta," *Bull. Am. Assoc. Petroleum Geol.* **37** **[5]** 1067-74, May (1953).

5. F. P. Shepard, "Revised Nomenclature for Depositional Coastal Features," *Bull. Am. Assoc. Petroleum Geol.* **36** **[10]** 1902-12, Oct. (1952).

6. F. P. Shepard, "Sedimentation Rates in Texas Estuaries and Lagoons," *Bull. Am. Assoc. Petroleum Geol.* **37** **[8]** (1953).

### Published Abstracts

1. Symposium on Sedimentation, Geological Socy. of America, 65th Annual Meeting, *Bull. Geol. Soc. Amer.* **63** **[12]** Dec. (1952).

*a.* F. P. Shepard, "Depositional Environment Characteristics Along the Gulf Coast, Part 1: Project Description and Rockport Texas, Area," p. 1297.

*b.* P. C. Scruton and D. G. Moore, "Depositional Environment Characteristics Along the Gulf Coast, Part 2: East Mississipp Delta Area," p. 1296.

2. Symposium on Finding Ancient Shorelines, Socy. of Economic Paleontologists and Mineralogists, 27th Annual Meeting, *J. Sediment. Petrol.* **23** **[2]** June (1953).

*a.* D. L. Inman and T. K. Chamberlain, "Particle-Size Distribution in Nearshore Environments," p. 127-8.

*b.* P. C. Scruton, "Distribution and Origin of Sediment Units in the Eastern Mississippi Delta," p. 125-6.

*c.* F. P. Shepard and D. G. Moore, "Sediment Zones Borderin the Barrier Islands of the Central Texas Coast," p. 126-7.

### Submitted for Publication

1. George Bien, "High-Frequency Titration of Micro-Quantitie of Chloride and Sulfate," submitted for publication to *Anal Chem.*

2. F. P. Shepard and D. G. Moore, "Sediment Zones Borderin the Barrier Islands of Central Texas Coast," *Socy. of Economi Paleontologists and Mineralogists, Spec. Publ. No. 3* (in press)

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*Printed in U.S.A.*

# ZOOLOGY.—Thysanopoda spinicaudata, *a new bathypelagic giant euphausi crustacean, with comparative notes on* T. cornuta *and* T. egregia.

Edwa Brinton, Scripps Institution of Oceanography,[1] La Jolla, Calif. (Commu cated by Fenner A. Chace, Jr.)

The bathypelagic giant euphausiids are taken here to include Crustacea belonging to the order Euphausiacea which live planktonically at great depths in the ocean, commonly below 2,000 meters. These giants among euphausiids are little known, probably owing to the fact that they are not abundant and live below the range of sampling of ordinary plankton-collecting gear. It is also possible that they are fast swimmers and are able to escape most nets. Together with *Thysanopoda spinicaudata*, n. sp., described below, the group includes at present only *Thysanopoda cornuta* Illig, 1905, and *T. egregia* Hansen, 1905. These euphausiids comprise a subdivision, "Group B," of the genus *Thysanopoda*, which was observed by H. J. Hansen (1912) to constitute a morphologically related unit. Four characters define this unit: a well-developed cervical groove separates the head area of the carapace from the thoracic region; the pseudoexopod of the first maxilla scarcely overreaches the outer margin of the joint, or does not overreach it at all; the endopod of the first maxilla is very long; the sixth abdominal somite is shorter than the fifth.

Euphausiids of this group are readily distinguished from other euphausiids, especially by means of the short sixth abdominal somite. Among the other species of Euphausiacea, only *Thysanopoda cristata* G. O. Sars, a midwater form which appears to be closely related to the giant euphausiids, possesses a sixth abdominal somite which is nearly as short as the fifth.

The euphausiids which live above a depth of about 500 meters are relatively small in size, reaching a maximum length of about 20 mm. There are two exceptions: the Antarctic *Euphausia superba* Dana which sometimes attains a length of 60 mm, and *Meganyctiphanes norvegica* (M. Sars) of the North Atlantic which reaches 40 mm. The euphausiids of the upper strata include numerous species belonging to nine gener
including one species *T. aequalis* Hanse
of Hansen's "Group A" of *Thysanopod*

The population which normally inhab
waters between about 500 and 2,000 mete
is characterized by fewer genera and speci
and by somewhat larger euphausiids. T
largest of these, which sometimes attain
length of 50 mm, are *Thysanopoda acutifro*
Holt and Tattersall, and *T. cristata* G.
Sars, both of which belong to Group A
*Thysanopoda*, and the monospecific *Benthe*
*phausia amblyops* (G. O. Sars).

The typical euphausiids below 2,0
meters are the bathypelagic giant eupha
siids which belong to Group B of *Thysan*
*poda. Bentheuphausia*, and some other sp
cies whose major concentration is in upp
layers, may, however, be present in this de
zone from time to time. The largest specim
in the Scripps Institution collections of t
bathypelagic giant *T. egregia* is an adu
female 62 mm long; the female specimen
*T. spinicaudata* measures 84 mm, and t
largest known specimen of *T. cornuta*, a ma
collected by the Scripps Institution ves
*Horizon* in the southeastern Gulf of Alask
is 95 mm long. These euphausiids not on
attain a somewhat greater length than t
Antarctic surface form *Euphausia superb*
but are also more broad. It is of interest
note, however, that both *E. superba* and t
bathypelagic giant euphausiids inhab
waters which are colder than 2–3°C.

It has been necessary to describe *T. spi*
*caudata* from a single specimen. This is f
to be justified in view of the extreme scarc
of animals of this group. *T. egregia* Hans
(1905), was described from a single specim
captured near the insular slope of the M
deira Islands, while *T. cornuta* Illig (190
was described from one animal from t
Wallfisch Ridge of the Southeastern Atla
tic. Illig (1905, 1930) and Hansen (19
1915) figure some of the features of
*cornuta*, while Hansen (1905) has drawn t
anterior part of *T. egregia*.

I am indebted to Prof. Martin W. Jo

---

[1] Contributions from Scripps Institution of Oceanography, new ser., no. 652.

son, under whose supervision a study of the Pacific euphausiids is being carried out, for his criticism and suggestions.

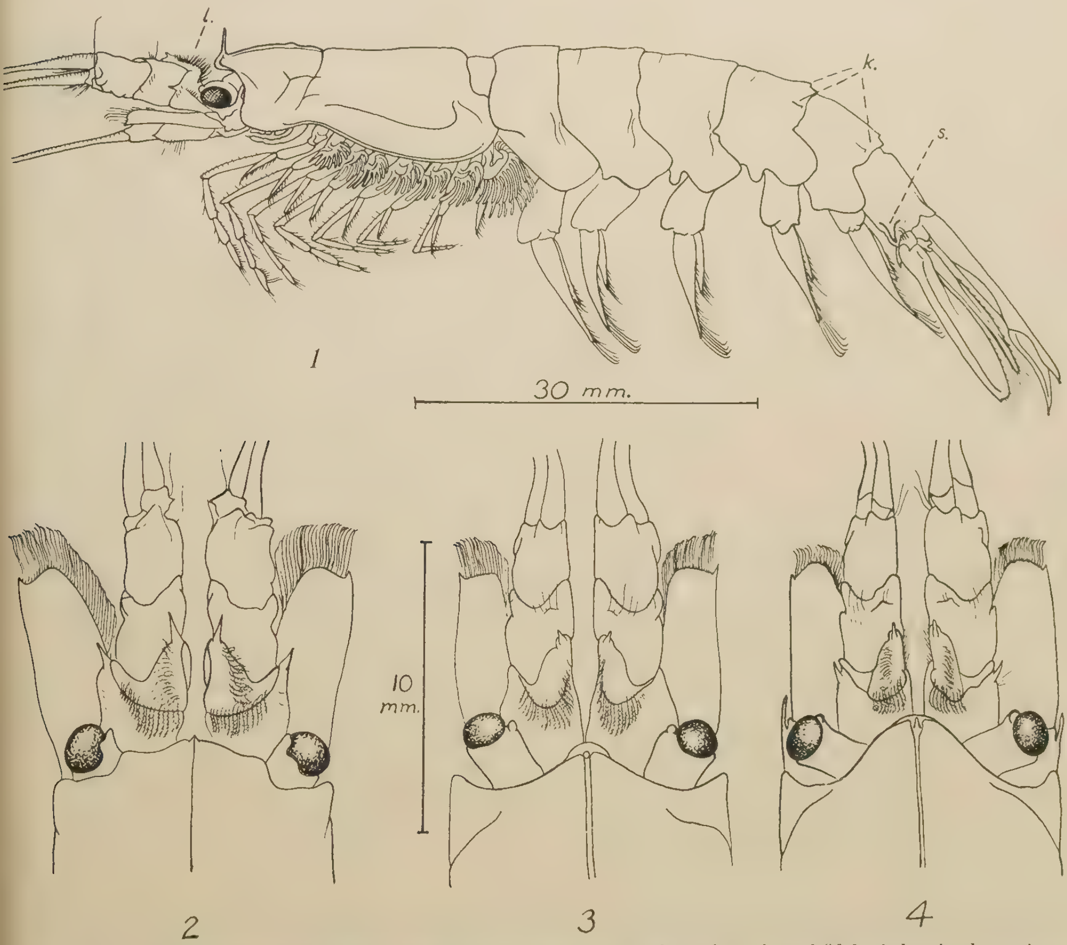
### **Thysanopoda spinicaudata**, n. sp.

Figs. 1, 3, 6, 10, 11

*Holotype.*—Female; length 84 mm.

*Diagnosis.*—The carapace is without lateral denticles in the adult. A cervical groove crosses the dorsal part of the carapace. Lateral furrows (Fig. 1) are continuous with the cervical groove A longitudinal submarginal ridge extends along the lateral margin of the carapace posterior to the subvertical grooves. The lateral limits of the carapace are thickened to form marginal ridges. Viewed dorsally (Fig. 3), the anterior margin of the carapace is slightly convex. The dorsal anterior end of the frontal plate is armed with a strong vertical spine 1.4 mm in length. A low middorsal keel is present on the carapace, extending from the vertical spine to the cervical groove. The keel is interrupted near its midpoint by a short, obtuse prominence. Viewed laterally, the thickness of the frontal plate is less than the length of the dorsal spine. The anterior margins of the frontal plate, lateral to the spine, are slightly upturned.

The proximal end of the lower flagellum of the first antenna carries a dense tuft of long, colorless setae. The heavily setose, raised dorsal area of the first article of the peduncle of the first antenna (Fig. 1, 3) is equipped terminally with an acute tooth which is bulbous at its base and which is directed upward and laterally. The setose



Figs. 1–4. —1, *Thysanopoda spinicaudata*, adult female: *k*, Keels on fourth and fifth abdominal somites; *l*, lappet on first article of antennular peduncle; *s*, spine on sixth abdominal somite. 2, *T. egregia*, anterior region, dorsal view. 3, *T. spinicaudata*, anterior region, dorsal view. 4, *T. cornuta*, anterior region, dorsal view.

part of the lappet of the first article is not produced posteriorly beyond its point of junction with the main part of the article; hence it does not overhang the trunk of the article. The scale of the second antenna is truncated distally (Fig. 3). A denticle is present at the antero-lateral angle.

*T. spinicaudata* derives its name from a heavy spine which is directed posteriorly and laterally from each side of the sixth abdominal somite (Fig. 1, s.). This spine orginates a short distance forward of the posterior margin of the somite and, together with that part of the pleuron adjacent to it, is situated so as to serve as a protective socket for the articulated base of the uropod.

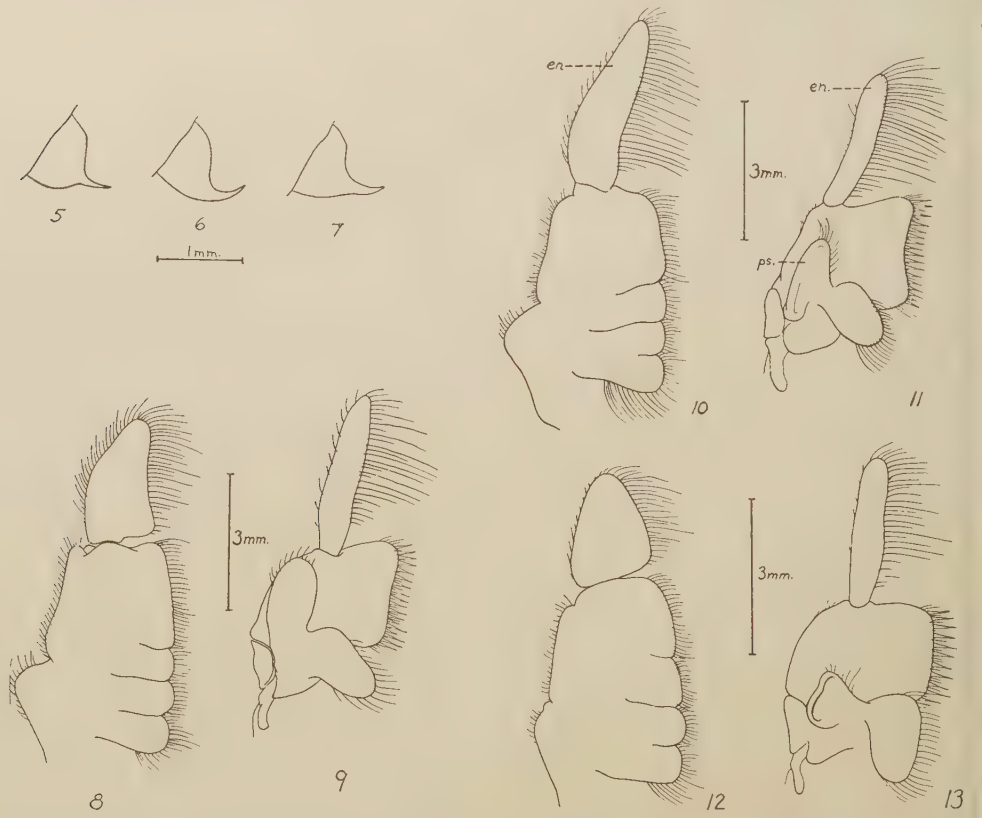
The pleura of the second abdominal segment are very slightly produced at the anterolateral angle, while those of the third and fourth segments are distinctly lobed. The pre-anal spine curves upward distally. Viewed laterally (Fig. 6), its lower margin traces a simple arc from the b
of the spine to the acute tip.

The endopod of the first maxilla (Fig. 11)
slightly convex in outline along its inner lon
tudinal border and concave on its outer marg
The pseudoexopod of the first maxilla bears
indentation on its slightly thickened ou
margin. The endopod of the second maxilla
very elongate (Fig. 10). The terminology for
mouthparts is that employed by Hansen (192

*T. spinicaudata* is brilliant red in color exc
for black eyes; white, richly arborescent gi
and tufts of fine, colorless setae at the bases
the outer flagella.

*Type specimen.*—The type specimen is
posited in the U. S. National Museum,
95677.

*Remarks.*—The frontal plate of this propos
new species is not produced anteriorly to
extent that it is in *T. cornuta* (Fig. 4), nor is
so obtuse, when viewed dorsally, as in *T. egreg*



Figs. 5–13.—5, *Thysanopoda cornuta*, pre-anal spine. 6, *T. spinicaudata*, pre-anal spine. 7 *egregia*, pre-anal spine. 8, *T. cornuta*, left second maxilla. 9, *T. cornuta*, left first maxilla. *T. spinicaudata*, left second maxilla. *en.*, endopod. 11, *T. spinicaudata*, left first maxilla; *en.*, en pod; *ps*, pseudoexopod. 12, *T. egregia*, left second maxilla. 13, *T. egregia*, left first maxilla.

A small tubercle, comparable to but much smaller than the dorsal spine of *T. spinicaudata*, is present on the frontal plate of *T. cornuta.* Seen laterally, the thickness of the frontal plate of *T. cornuta* is much greater than the length of the tubercle. The frontal plate of *T. egregia* is curved downward. The middorsal keel on the carapace of *T. cornuta*, anterior to the cervical groove, is higher and more massive than in *T. spinicaudata*, while in *T. egregia* it is lower, broader, and poorly defined.

The proximal end of the lower flagellum of the first antenna of the males of *T. cornuta* and *T. egregia* is much thicker than that of the females of these two species and of *T. spinicaudata*. However, in each of the species the end carries a tuft of long setae which is more dense in males of *T. cornuta* and *T. egregia* than in females.

In *T. cornuta* and *T. egregia* the setose lappet of the first article of the peduncle of the first antenna is produced posteriorly, and slightly overhangs the trunk of the article. In the same two species, the distal margin of the scale of the second antenna is convex, when viewed dorsally (Figs. 2, 4), while in *T. spinicaudata* it is obtuse or truncated.

The fourth and fifth abdominal somites in all three species each bear three abbreviated keels: a mid-dorsal keel, flanked by a pair of subdorsal keels (Fig. 1). The posterior dorsal surface of the sixth somite is hollowed, forming a dorsolateral ridge along each side of the posterior half of the somite.

The ventral margins of the pre-anal spines of *T. egregia* and *T. cornuta* are indented (Figs. 5, 7), while in *T. spinicaudata* this margin is convex. The spines in the two former species show no sexual dimorphism.

Distinctions between these allied species are found also in details of mouthpart structure. The pseudoexopod of the first maxilla of *T. egregia* (Fig. 13) is, as in *T. spinicaudata*, slightly thickened along its outer margin. It is also indented near the midpoint of that margin, while the same margin of the pseudoexopod of *T. spinicaudata* is entirely convex. The pseudoexopod of the first maxilla of *T. cornuta* (Fig. 9) is flat and reaches to the outer margin of its joints.

The endopod of the second maxilla of *T. egregia* (Fig. 12) and of *T. cornuta* (Fig. 8) is half again as long as it is wide. The entire margin is convex in outline in *T. egregia*, while the inner margin of the same endopod of *T. cornuta* is concave in profile.

Larvae tentatively assigned to *T. cornuta* by Illig (1930) and Zimmer (1914) possess spiniform processes at the subdorsal posterior margins of the sixth abdominal somites. Compared with the latero-ventral spines which are subterminal to the sixth segment of *T. spinicaudata*, these are dorsolaterally situated and are present only in the larval (furcilia) stages of *T. cornuta*. The Scripps collections contain a series of the larvae which have the spiniform processes. Observations upon the development of the lateral groove complex on the carapace and of the tubercle on the frontal plate of the carapace indicate that these larvae belong to *T. cornuta*.

*Type locality and collecting gear.*—*T. spinicaudata* was collected by use of the Isaacs-Kidd Midwater Trawl at 2,200 meters in 4,070 meters of water, between 25°52′N, 114°40′W, and 26°00′N, 114°24′W. This is 75 miles west of the Baja California continental slope, adjacent to the southern shoulder of Rosa Bank.

*Distribution.*—*T. cornuta* and *T. egregia* have been taken at depths of 1,100–6,000 meters in the Atlantic, Pacific, and Indian Oceans. Larvae are known from 150–1,500 meters. *T. spinicaudata*, taken at 2,200 meters, probably has ecological requirements similar to those of the other two species. Extensive sampling in the Northeastern Pacific by Scripps Institution vessels indicates that the giant forms occur in deep waters seaward of continental shelves and borderland areas.

## REFERENCES

Hansen, H. J. *Preliminary report on the Schizopoda collected by H. S. H. Prince Albert of Monaco during the cruise of the* Princesse-Alice *in the year 1904.* Bull. Inst. Oceanogr. Monaco, no. 30: 32 pp., 24 figs. 1905.

———. *The Schizopoda. Reports on the scientific results of the expedition to the tropical Pacific, in charge of Alex. Agassiz, by the U. S. Fish Commission steamer* Albatross . . . Mem. Mus. Comp. Zool. **35**: 173–296, pls. 1–12. 1912.

———. *Studies on Arthropoda II (Crustacea)*: 1–176, 8 pls. Copenhagen, 1925.

Illig, G. *Eine neue Art der Gattung* Thysanopoda. Zool. Anz. **28**: 663–664, 3 figs. 1905.

———. *Die Schizopoden der Deutschen Tiefsee-Expedition.* Deutsche Tiefsee Expedition, 1898–99, **22**(6): 379–625, 215 figs. 1930.

Tattersall, W. M. *Crustaceans of the orders Eu-*

*phausiacea and Mysidacea from the Western Atlantic*. Proc. U. S. Nat. Mus., **69**(8): 1–31, pls. 1–2. 1926.

———. *The Euphausiacea and Mysidacea of the John Murray Expedition to the Indian Ocean.* The John Murray Expedition, 1933–34, Sc entific Reports **5**(8): 203–246, 21 figs. 1939.

Zimmer, C. *Die Schizopoden der Deutschen Süd polar Expedition, 1901–1903.* Deutsche Süd polar-Expedition **15**(4): 377–445, 4 pls. 1914.

# DEPOSITION OF EVAPORITES

BY

P. C. SCRUTON

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 37, NO. 11 (NOVEMBER, 1953), PP. 2498-2512, 4 FIGS., 2 TABLES

# DEPOSITION OF EVAPORITES[1]

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## ABSTRACT

Modern oceanographic studies in estuaries and other restricted arms of the sea have shown that a characteristic circulation pattern exists. Surface currents flow from regions of low salinity to regions of higher salinity in response to hydrostatic head and are accompanied at depth by oppositely directed currents flowing from high to low salinity regions because of density distribution. Salts are deposited in restricted estuaries where evaporation exceeds precipitation plus runoff. The necessary restrictions of the estuary or basin are in part dynamic and in part static. Dynamic restriction is caused by the hydrostatic head and by frictional stresses between the oppositely directed surface and bottom currents, and between the bottom current and the channel floor. Static restriction is produced by topographic confinement.

When high concentrations are developed a strong horizontal salinity gradient exists which produces lateral segregation of different salts during precipitation. The escaping deep current returns to the sea those salts which have not been precipitated. Fluctuations in equilibrium caused principally by changes in excess of evaporation or in degree of channel closure cause migrations of the horizontal salinity gradient along the longitudinal axis of the basin which produce vertical differentiation of salts. The order in which salts occur in the vertical column can be predicted from oceanographic and chemical data and agrees well with many vertical sequences which have been described.

## INTRODUCTION

A problem which has interested geologists for many years is the deposition of thick beds of salts. The ocean is recognized to be the source of the salts which form the more common deposits, and their origin is of oceanographic as well as geologic interest. The purposes of this report are: (1) to describe certain hydrographic conditions in estuaries in both humid and arid regions which have been found by recent oceanographic studies, (2) to utilize this experience to elaborate on known characteristics of salt-depositing evaporating pans, and (3) to infer a depositional sequence of evaporites which suggests explanations for some of the features of known beds.

Ochsenius (1888) was one of the first workers to develop an hypothesis to explain salt deposits, and his now-famous bar theory has become a classic. Later workers, such as Branson (1915) and R. H. King (1947), have proposed modifications to this theory which seemed necessary to explain relationships which they observed.

Many workers have been troubled by the volume ratio of $CaSO_4$:NaCl of about 1:1 which exists in the Permian Castile beds of West Texas and southeast New Mexico. This ratio is not in agreement with the ratio of approximately 1:30 which would exist if normal sea water were completely evaporated. King (1947, pp. 470–71) explained the discrepancy as follows: the deep Permian Delaware

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[2] Scripps Institution of Oceanography, University of California. During its preparation the manuscript was critically read by R. S. Arthur, G. S. Bien, M. N. Bramlette, F. B Phleger, R. R. Revelle, and F. P. Shepard, all of the Scripps Institution. Their helpful comments and suggestions are gratefully acknowledged.

basin of Texas and New Mexico, an arid region where evaporation exceeded precipitation plus runoff, was connected to the open sea by a restricted channel on the southwest. The water within this basin below what he inferred to be average wave base consisted of a uniform brine formed by the excess of evaporation. Normal marine water flowing into the basin through the restricted channel, replaced that lost by the excessive evaporation, moved over the uniform brine toward the distal end of the basin, and was concentrated by evaporation until it became similar in density to the brine below. It then mingled with the brine and sank. To compensate for the volume of sinking brine at the basin's upper end, he suggested that a continuous seaward flow of dense hypersaline water, a "reflux" from the basin, took place in the bottom of the channel below average wave base. King's hypothesis was developed to account for geological relationships; he believed a process of this type was necessary to remove the excess sodium chloride in sea water from the basin and establish the observed volume ratio of $CaSO_4$:NaCl.

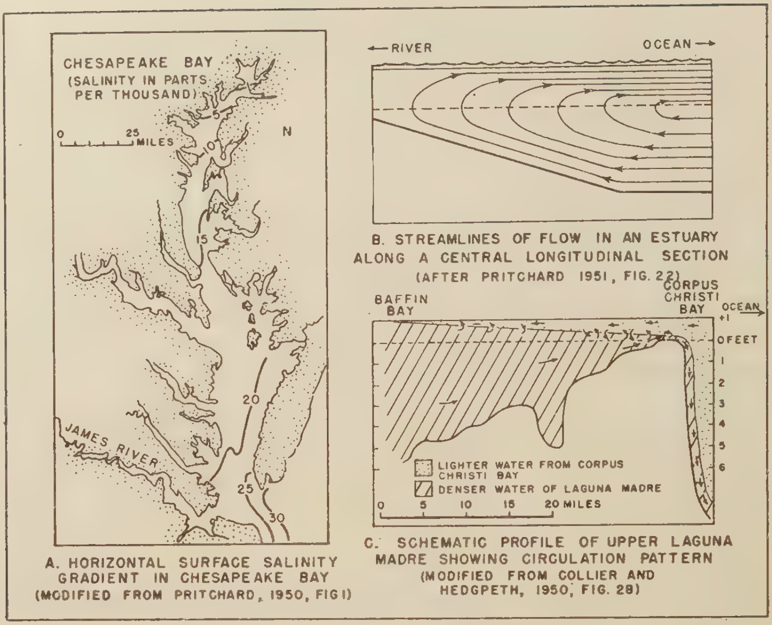
In recent years much work has been done to establish the flow characteristics and distribution of properties in estuaries, inlets, and other bodies of water partly restricted from the open sea. Studies of this type furnish information which can be utilized to increase understanding of factors leading to formation of evaporites.

## OCEANOGRAPHIC DATA

Most recent studies of restricted arms of the sea are in humid areas where fresh water is introduced in quantity to the sea, so that precipitation and runoff exceed evaporation. Stommel and Farmer (1952b) have compiled numerous data from these sources. Among many other notable studies in this type of region, those conducted by Tully (1937, 1949), Redfield (1950), Ketchum (1951), and Pritchard (1950, 1951) are good examples.

These studies have shown that in an estuary or lagoon with a source of fresh water in the upper end, a horizontal surface salinity gradient exists with salinity increasing seaward. In longitudinal section of the estuary, current and salinity measurements show this gradient to be associated with seaward flow of less saline water at the surface accompanied by landward flow of more saline water beneath. Mixing between these opposing currents occurs in the zone of contact and is accompanied by erosion of the deeper layer. Thus volume and salinity of surface water increase seaward and of the deeper water decrease landward. Mixing may occur between fresh and sea water directly, or it may involve the formation of an intermediate water type which is later remixed, so that more complicated relationships are displayed (Redfield, 1950). Figure 1 shows the nature of some of the relationships which have been found.

From their studies Stommel and Farmer (1952b) have classified estuaries in humid regions on the basis of the degree to which these vertical and horizontal salinity and current characteristics are shown and have recognized four general


CHESAPEAKE BAY
(SALINITY IN PARTS PER THOUSAND)
0 25 MILES
N
5
10
15
20
25
30
JAMES RIVER
RIVER
OCEAN
BAFFIN BAY
CORPUS CHRISTI BAY
OCEAN
+1
0 FEET
1
2
3
4
5
6
LIGHTER WATER FROM CORPUS CHRISTI BAY
DENSER WATER OF LAGUNA MADRE
0 5 10 15 20 MILES

A. HORIZONTAL SURFACE SALINITY GRADIENT IN CHESAPEAKE BAY (MODIFIED FROM PRITCHARD, 1950, FIG 1)

B. STREAMLINES OF FLOW IN AN ESTUARY ALONG A CENTRAL LONGITUDINAL SECTION (AFTER PRITCHARD 1951, FIG. 22)

C. SCHEMATIC PROFILE OF UPPER LAGUNA MADRE SHOWING CIRCULATION PATTERN (MODIFIED FROM COLLIER AND HEDGPETH, 1950, FIG. 28)

Fig. 1

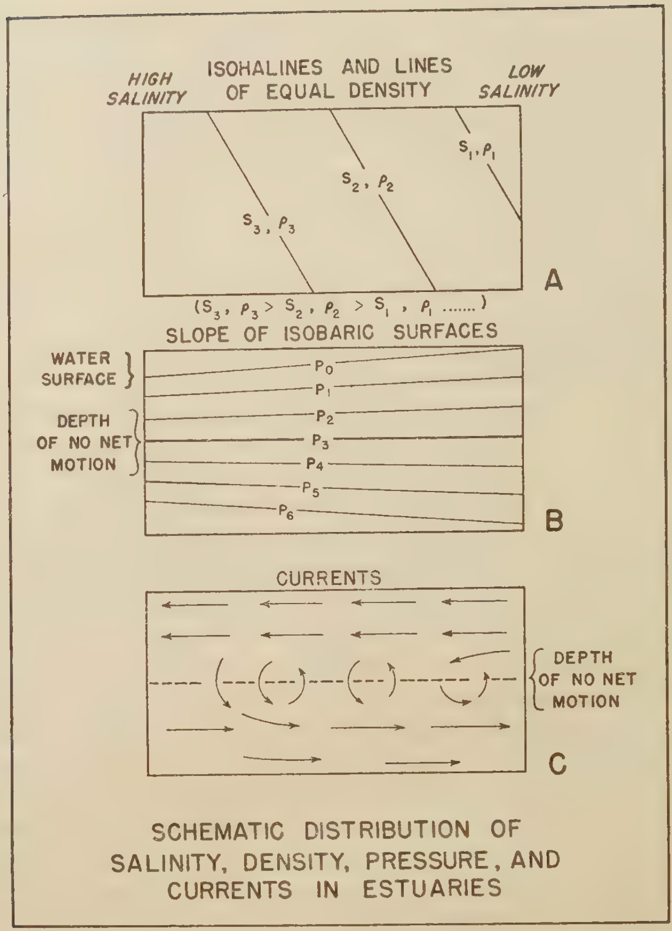
types. These are as follows. 1. The vertically mixed estuary which shows a horizontal salinity gradient but a minimum of vertical differentiation of water types; the Severn and Raritan rivers are samples. 2. The slightly stratified estuary of which the James River is an example. 3. The highly stratified estuary exemplified by Alberni Inlet. 4. The salt-wedge estuary, a type found at the mouths of strong rivers where the vertical flow and salinity characteristics are best developed and where a salt wedge may extend far upstream. The Mississippi River is an example of this type. In the Mississippi River, Russell (1936), Rhodes (1950), and Simmons (1952) have shown that the distance upstream to which the salt wedge extends is a function of volume of river discharge. During periods of low discharge a small frictional stress is exerted by the superjacent fresh water on the salt wedge, the rate of mixing between the two layers is not great, and the wedge may extend at least 135 miles upstream (Simmons, 1952, p. 70; Russell, 1936, p. 94). Under conditions of high discharge, however, the wedge may be expelled from the river mouth.

There are few studies of estuaries in regions where evaporation exceeds precipitation plus runoff. A group at the Scripps Institution of Oceanography under the direction of G. C. Ewing (Ewing, 1950) investigated the hydrography of San Diego Bay, an evaporation basin during the summer. Collier and Hedgpeth (1950) reported on a series of surface salinities collected in Laguna Madre and Baffin Bay, evaporating pans on the southern Texas coast. The marked salinity gradients in these inlets exist because of the excess of evaporation, so that salinities increase away from the source of normal sea water. Zenkevich (1947) reports a similar salinity distribution in the Sivash (Putrid) Sea, an arm of the Sea of Azov, which he also attributes to excessive evaporation.

Data derived from the San Diego Bay study indicate the existence of a surface drift toward the restricted end of the bay caused by a surface slope produced by excessive evaporation in the bay. Associated with the surface drift is a return, seaward directed, bottom current which is the result of increased density due to concentration of salts in the restricted area of the bay. Collier and Hedgpeth (1950, Fig. 28) deduced a similar system from their observations in Laguna Madre (Figure 1-C). The Mediterranean and Red seas (Sverdrup *et al.*, 1946) provide well known examples of surface currents flowing through restricted channels into evaporating pans with return currents to the open sea of more dense saline water resulting from concentration of salts flowing outward beneath. Sinking of the oxygenated, highly saline, surface waters prevents stagnation of the deep basins (Sverdrup *et al.*, 1946, pp. 649–50).

Although currents and salinity gradients in estuaries in regions of excessive or deficient evaporation are opposite in direction with respect to a fixed point on the estuary, controlling dynamics in the two systems are the same. This can be appreciated if consideration is confined to the relationship between the flow pattern and the salinity and density gradients. In both types of estuaries the surface current flows in the direction of increasing salinity and the bottom current flows toward water of lower salinity. Figures 1 and 2 illustrate this concept. Both Hedgpeth (1953) and Pritchard (personal communication) also have recognized this basic similarity. The vertical pattern of flow in estuaries of either type is a product of surface slope caused by either excessive evaporation or excessive precipitation plus runoff and slope of isobaric surfaces at depth caused by horizontal and vertical density differences. Density differences in these water bodies are caused chiefly by salinity differences (Pritchard, 1951, p. 33), but temperature exerts some effect. Because of the basic similarity of the two types of estuaries, hydrographic characteristics established for one may be applied directly to the elucidation of the characteristics of the other. Figure 2 gives schematically the vertical distributions of salinity, density (A), pressure (B), and currents (C) to be expected in water bodies of either type.

In general, factors which appear to be most important in determining the hydrographic character of estuaries and similar bodies of water are: (1) the balance between amount of fresh water introduced and the amount of evaporation, (2) the depth and configuration of the bottom of the estuary including the sill or bar, and (3) local conditions of wind, temperature, and tides. Conditions of quasi-equilibrium between precipitation, evaporation, and flow to and from the sea tend to be established. Such an equilibrium results in a relatively stable position of the horizontal salinity gradient. Modifications to the equilibrium or steady state conditions are produced, however, by long term as well as seasonal variations in precipitation, temperature, winds, and sea-level changes (Collier and


HIGH SALINITY
ISOHALINES AND LINES OF EQUAL DENSITY
LOW SALINITY
$S_1, \rho_1$
$S_2, \rho_2$
$S_3, \rho_3$
A
$(S_3, \rho_3 > S_2, \rho_2 > S_1, \rho_1 \ldots\ldots)$
SLOPE OF ISOBARIC SURFACES
WATER SURFACE
DEPTH OF NO NET MOTION
$P_0$
$P_1$
$P_2$
$P_3$
$P_4$
$P_5$
$P_6$
B
CURRENTS
DEPTH OF NO NET MOTION
C

SCHEMATIC DISTRIBUTION OF SALINITY, DENSITY, PRESSURE, AND CURRENTS IN ESTUARIES

FIG. 2

Hedgpeth, 1950; Pritchard, 1950, 1951), so that the horizontal salinity gradient fluctuates along the longitudinal axis of the basin (on a long term or seasonal basis).

The results of these numerous investigations of estuaries and large evaporation basins amply confirm the basic pattern of circulation suggested in King's general reflux hypothesis. In addition, however, they can be used, together with other data, to extend the hypothesis and to suggest explanations for many of the mineralogic and lithologic variations which are found in evaporite sequences.

### CHEMICAL DATA

Usiglio's experiments on evaporation of sea water furnish, so far as is known, the only existing chemical data basic to the entire evaporite problem. Table 1,

Table I. Approximate Limiting Density and Salinity Values within Which Various Salts Precipitate from Solution

(From Clarke, 1924, p. 220)

| *Salt* | *Lower Limit* | | *Upper Limit* | |
|---|---|---|---|---|
| | *Density* | *Salinity Parts Per Thousand* | *Density* | *Salinity Parts Per Thousand* |
| Calcium carbonate | 1.0500 | 72 | 1.1264 | 199 |
| Calcium sulphate | 1.1264 | 199 | 1.2015 | 332 |
| Calcium sulphate and sodium chloride | 1.2138 | 353 | 1.2570 | 427 |
| Sodium chloride | 1.2778 | 457 | 1.3069 | 523 |
| Magnesium sulphate | 1.2138 | 353 | 1.3069 | 523 |

prepared from these data (Clarke, 1924, p. 220), shows that individual salts tend to be precipitated within a unique salinity and density range. If density values associated with the salinities at which salts are precipitated are substituted in Figure 2-B, isopycnal distribution in a salt-depositing evaporating pan can be reconstructed. Since the density is principally a function of dissolved salts, the isopycnals also can be considered lines of equal salt content. Figures 3 and 4 show how this salinity and density distribution tends to produce deposits of relatively pure salts on the bottom underlying the salinity (density) range within which the particular salt is precipitated (Lang, 1937, pp. 885–88; Hills, 1942; Adams and Frenzel, 1950).

## THEORY

Deposition of a salt from sea water requires that the concentration be increased until the solubility product of the salt is exceeded. This can be accomplished on a large scale in nature only by evaporation in areas where restrictions to free circulation exist and normally where evaporation exceeds precipitation plus runoff for a relatively long period of time.

When conditions of excess evaporation over precipitation plus runoff exist, a slope of the water surface develops causing a basinward flow of sea water due to hydrostatic pressure. If conditions remain uniform, an approximate equilibrium between input of fresh and salt water and outflow of bottom water will be established. With the establishment of equilibrium, salinity characteristics do not change, and the horizontal gradient does not shift markedly within the basin.

Restriction to escape of the deep water of the basin is necessary for high salt content to be developed. Such restriction of a static nature is imposed by a sill or similar physical barrier. Dynamic restrictions to escape of deep water also exist, however. Hydrostatic head induces a flow toward the basin head throughout the vertical water column. To counterbalance this flow horizontal density differences (principally the result of salinity differences) are established so that the pressure surfaces at depth slope toward the basin entrance (Fig. 2). The field of pressure produced by hydrostatic head must be exceeded at depth by the

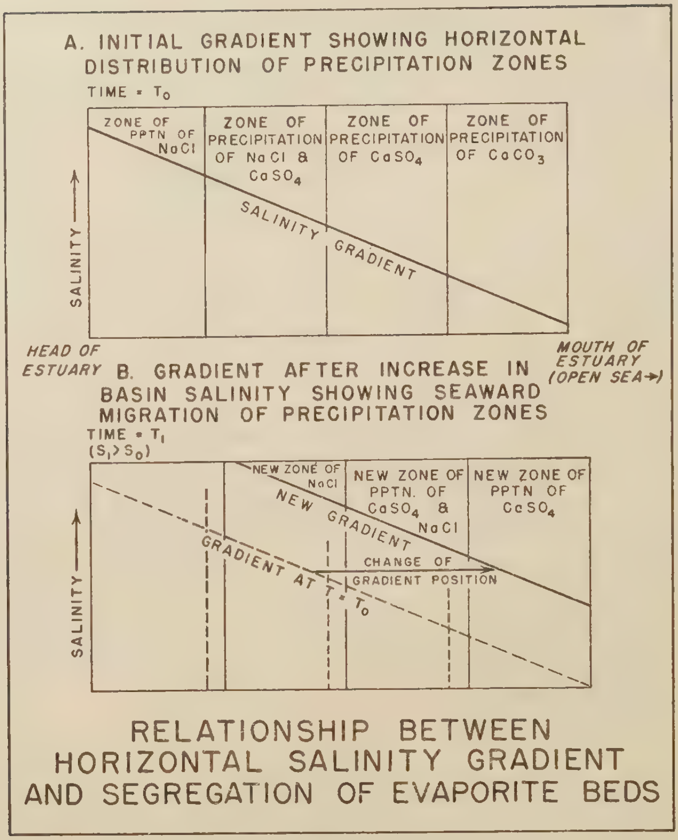

A. INITIAL GRADIENT SHOWING HORIZONTAL DISTRIBUTION OF PRECIPITATION ZONES
TIME = $T_0$
ZONE OF PPTN OF NaCl
ZONE OF PRECIPITATION OF NaCl & $CaSO_4$
ZONE OF PRECIPITATION OF $CaSO_4$
ZONE OF PRECIPITATION OF $CaCO_3$
SALINITY GRADIENT
SALINITY
HEAD OF ESTUARY
MOUTH OF ESTUARY (OPEN SEA→)
B. GRADIENT AFTER INCREASE IN BASIN SALINITY SHOWING SEAWARD MIGRATION OF PRECIPITATION ZONES
TIME = $T_1$
($S_1 > S_0$)
NEW ZONE OF NaCl
NEW ZONE OF PPTN. OF $CaSO_4$ & NaCl
NEW ZONE OF PPTN OF $CaSO_4$
NEW GRADIENT
GRADIENT AT T = $T_0$
CHANGE OF GRADIENT POSITION
SALINITY
RELATIONSHIP BETWEEN HORIZONTAL SALINITY GRADIENT AND SEGREGATION OF EVAPORITE BEDS

FIG. 3

pressure field due to density. In addition, under conditions of strong stratification in the entrance channel and high rate of surface inflow into a basin caused by a large amount of evaporation, another type of dynamic barrier to brine escape exists. Data from study of the Mississippi River (Rhodes, 1950; Simmons, 1952) have shown that a large flow of fresh water imposes a dynamic barrier to intrusion of salt water because of friction at their interface. Flume experiments on a two layer system at constant volume of surface discharge conducted by Stommel and Farmer (1952a) show the effectiveness of this dynamic barrier to salt water intrusion is increased by constriction of the channel. Similarly, when surface water flows into an evaporation basin, escape of deep brine is inhibited by the establishment of this type of barrier. Existence of a dynamic barrier of this type is not only an observed feature of the flow pattern but may be essential to entrapment of the brine. The effectiveness or completeness of these dynamic barriers is related to both amount of excess of evaporation and degree of restriction of the connecting channel. For this reason, the basin salt, or density, equilibrium must

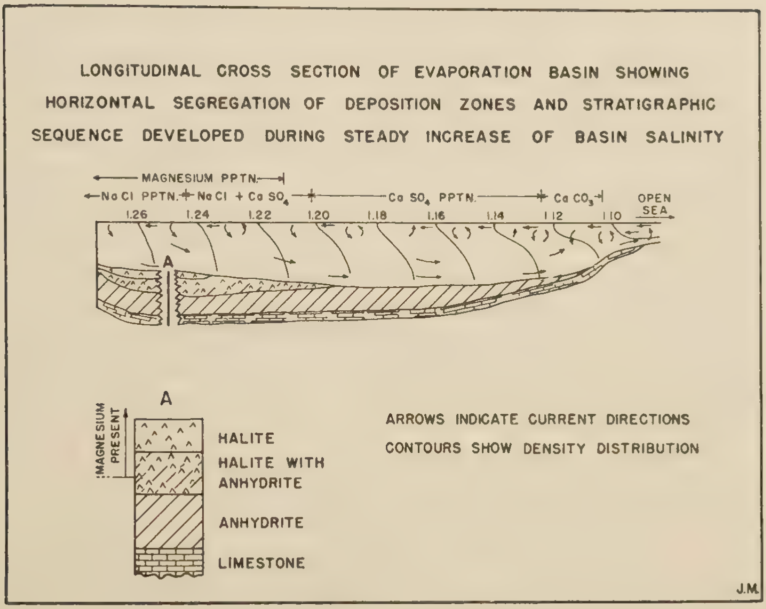

LONGITUDINAL CROSS SECTION OF EVAPORATION BASIN SHOWING HORIZONTAL SEGREGATION OF DEPOSITION ZONES AND STRATIGRAPHIC SEQUENCE DEVELOPED DURING STEADY INCREASE OF BASIN SALINITY
MAGNESIUM PPTN.
NaCl PPTN.
NaCl + CaSO4
CaSO4 PPTN.
CaCO3
OPEN SEA
1.26
1.24
1.22
1.20
1.18
1.16
1.14
1.12
1.10
A
A
MAGNESIUM PRESENT
HALITE
HALITE WITH ANHYDRITE
ANHYDRITE
LIMESTONE
ARROWS INDICATE CURRENT DIRECTIONS
CONTOURS SHOW DENSITY DISTRIBUTION
J.M.

FIG. 4

be considered a dynamic equilibrium which is principally sensitive to fluctuations in these factors. Small scale shifts in equilibrium can be produced by changes in density due to temperature or sea-level variations and by changes in wind stress.

## INFERRED PROCESS

The foregoing background information, derived from studies of circulation in estuaries and evaporation basins, chemical experiment, and theoretical consideration, permits a general reconstruction of events and circumstances leading to evaporite deposition.

An excessive rate of evaporation removes water from the restricted basin, causes a slope of the sea surface to develop and a continuous flow of additional water from the ocean to enter the basin in response to this surface slope. At the initiation of the process, basin water has a relatively low and uniform density and therefore concentration of surface water is required to establish strong gradients. A current of dense water flowing to the sea commences when the slope of pressure surfaces at depth (Fig. 2) due to excess density creates a potential for flow which exceeds the hydrostatic head. After this flow is established, the potential also must overcome topographic restraint, bottom friction, and, where strong vertical stratification exists, frictional forces between the oppositely directed currents. Stirring and mixing occur between the surface inflowing water and the outflowing bottom water because of turbulence and friction between the two currents, and takes place at a higher rate in restrictions of the channel. This produces a modification in the character of each of these waters, an increase in the salinity of the surface water and a decrease in the salinity of the bottom water. Thus, soon after the process is initiated, the inflowing current transports water to the basin which is more concentrated than the normal marine water originally flowing from the open sea. This effect may be present at a considerable distance seaward from the basin if the channel is long. The restrictions imposed on the bottom flow are such that free circulation does not develop, and an increase in salinity and density of basin water takes place until conditions of approximate dynamic equilibrium are achieved.

When salinities are high in the inflowing surface water due to mixing, destruction of organisms being swept in will result. Their shells tend to be returned toward the open sea on settling to the bottom, however, because of the seaward directed bottom current.

The hydrographic characteristics of a large basin could be expected to change from a type similar to the salt-wedge river estuary near the entrance to one comparable with the vertically mixed estuary at the basin head as the density differences between surface and deep waters decreased (Fig. 4). The inflowing surface water is concentrated as it flows toward the distal portions of the basin by both evaporation and continued mixing with more saline waters. Because the distal portions of the basin in general contain water of highest salt content, deposition of evaporites is initiated in these regions when the solution is sufficiently concentrated. This seems to be especially true if the distal portions of the basin are large.

Table I shows the approximate order in which the most common evaporites would begin to be formed. Usiglio's order of precipitation indicates that the first material to be deposited would be iron oxide (not shown in Table I). As the water becomes more concentrated, the zone of iron oxide precipitation moves toward the entrance of the basin, and calcium carbonate is precipitated in the distal portion (Figs. 3, 4). Further concentration results in calcium sulphate coming from solution in the distal portion and an entrance-ward movement of the zone of calcium carbonate precipitation. Still greater concentration of the water brings sodium chloride from solution in the distal region. Thus, a vertical section through the resulting deposit would show, at the base, beds containing iron oxide overlain in ascending order by limestone, gypsum or anhydrite, and rock salt, initially with some $CaSO_4$, later containing more magnesium. Deviation from this order can be anticipated, however, since the data of Usiglio give no more than an indication of the order of precipitation. At no place in an evaporation basin could the water be expected to retain "normal marine" ionic ratios existing at the time. Protracted precipitation in the basin and mixing and recycling in the channel and basin tend to concentrate the more soluble ions. Surface drainage in different regions also varies in chemical character. In addition, at high concentrations temperature changes are of great importance in determining character of precipitated material.

Since quasi-equilibrium conditions can be established at any concentration and thus stabilize the position of the horizontal salinity gradient, the thickness of each unit could be a measure of the length of time the material in question was being precipitated over the particular bottom. Furthermore, since the salts are isolated into zones of deposition by differences in solubility products, a longitudinal profile of the basin with the entrance at the origin would show the same sequence. Figure 4 shows horizontal segregation of the deposits and the nature of the inferred vertical sequence.

Seasonal or long-term variations in rainfall such as described by Judson (1952) in the southwestern United States, variations in temperature or sea-level altering the density structure, or variations of wind are capable of altering the equilibrium conditions and causing horizontal movement of the position of the depositing zones. Such movements cause the character of precipitating salt at any point to change.

## GEOLOGICAL DATA

It is important to subject the inferred mechanism for producing a migrating salinity gradient to a geological test. This can not be accomplished directly. However, if it is assumed that the channel cross section remained constant and the fluctuations occurred in the excess of evaporation, comparison of the hypothetical sequence of beds which would result with actual sequences described in the literature affords some check.

Stewart (1951a, b) recently has published the results of detailed analyses of cores penetrating the Permian evaporite sequence of Yorkshire, England. Three cycles of deposition are represented, with the middle zone being the most complete. Stewart's generalized subdivision of this zone is as follows (1951a, p. 446).

Top 1. Upper Halite zone
2. Halite-Sylvine zone
3. Halite zone*
4. Halite-Anhydrite zone
5. Anhydrite zone
6. Dolomite zone (upper Magnesian limestone)

* Magnesite is present in the sequence above the middle of this zone, with the lower part containing layers of halite and anhydrite.

This sequence is described in detail and furnishes excellent agreement with the hypothetical sequence. The top Halite zone suggests a migration of the salinity gradient toward the distal portion of the basin following deposition of the Halite-Sylvine zone.

The Permian salt section of Germany (Barton, 1925a, b; Brown, 1934) shown in Table II indicates fluctuating salinity conditions with maxima during deposition of the "Older" potash beds, the "Younger" rock salt, and the "Youngest" rock salt. A considerable break in sedimentation is suggested above the "Older" potash beds. Increase of salinity to a maximum followed by a decrease as indicated by a change in the type of salt also is shown in the German Triassic (Brown, 1934, p. 1245), the Silurian of New York (Phalen, 1919, pp. 55, 57), the

Table II. Normal Permian Evaporite Sequence of Middle Leine Valley, Germany
(After Barton, 1925b, p. 1248)

| | *Meters* | |
|---|---|---|
| Upper Zechstein clays | 20 | Massive redbed clay with anhydrite nodules and basal bed of anhydrite |
| "Youngest" Rock Salt | 50–60 | Rock salt |
| "Pegmatite" Anhydrite | 1–2.5 | Anhydrite with scattered intergrown salt crystals |
| Red Salt Clay | 20–25 | Massive red clay with anhydrite nodules |
| "Younger" Rock Salt | 145–70 | Rock salt with some polyhalite and anhydrite |
| "Main" Anhydrite | 20–40 | Massive anhydrite, no bedding |
| "Gray" Salt Clay | 4.5 | Clay, dolomitic marl, anhydrite, uniform |
| "Older" Potash beds | 8 | 55% carnallite, 26% rock salt, 17% kieserite |
| Transition zone | 13 | Rock salt and kieserite |
| "Older" Rock Salt | 70 | Rock salt with anhydrite beds; 94% rock salt, 6% anhydrite |
| "Lower" Anhydrite (present in normal Stassfurt section) | 70–100 | Anhydrite with intercalations of bituminous dolomitic beds and 1 or 2 rock salt beds |

Silurian of Michigan (Stone *et al.*, 1920, pp. 216–17), and the Permian of Oklahoma (Muir, 1934, pp. 1300–02). Each of these sections can be explained on the basis of fluctuating salt content caused by changes in the evaporation-precipitation budget.

Similar agreement with the hypothetical sequence seems to be indicated by the often-repeated cycle of deposits described by Schaller and Henderson (1932, pp. 8–14) from the potash fields of Texas and New Mexico. This cycle consists of the following.

Top 1. Nearly pure halite
2. Halite (plus some polyhalite)
3. Polyhalite
4. Anhydrite
5. Clay (commonly iron-rich, see Henderson, pp. 24–26)
(Zones 4 and 5 may contain magnesite as well.)

They also attribute genetic significance to the cycle because of its common occurrence (1932, p. 8) and suggest that the polyhalite is formed subsequent to deposition by replacement. However, the possibility of this mineral being primary and resulting from the co-precipitation of magnesium, calcium, and potassium sulphates in concentrated solution with later some solution and redeposition should be considered (see Clarke, 1924, p. 227; Schaller and Henderson, 1932, p. 64, also Pls. 24, 26–33; Hill, 1937, p. 2243; Kroenlein, 1939, p. 1689; Posnjak, 1938, p. 270). From other descriptions of the Castile and overlying Salado formations (Lang, 1937; Kroenlein, 1939; P. B. King, 1942; Adams, 1944) it would appear that the general sequence which is found also corresponds with the inferred section. The Castile beds consist principally of laminated anhydrite in the southern (seaward) end of the basin overlying a thin limestone, but also contain thick halite deposits on the north. Overlying the Castile are the salt beds of the Salado formation. Fluctuations in equilibrium conditions with time producing migrations of the lines of equal salt content are indicated in the vertical column by changes from limestone[3] to anhydrite, to salt, to salt with anhydrite, to anhydrite with salt.

The Pennsylvanian Paradox formation of Colorado and Utah has been described by Baker, Dane, and Reeside (1933). Their most complete section, obtained from driller's records of the J. H. Shafer well No. 1 (1933, p. 969), also suggests general agreement with the hypothesis. Numerous black shales which have special significance occur between evaporite beds of the Paradox formation, however, and suggest extreme fluctuations in the precipitation-evaporation budget, salinity conditions, and the circulation pattern. A change from excess of evaporation to excess of precipitation plus runoff could result in a change from conditions of an oxygenated evaporation pan to those of an euxinic basin, an environment favorable to formation of black shales (Fleming and Revelle, 1939, pp. 95–102), within the same basin framework.

On a much smaller scale the fine lamination of the anhydrites of the Castile formation, consisting of alternations of anhydrite and bituminous calcite (Udden, 1924; Schaller and Henderson, 1932), seem to confirm the hypothesis and to suggest short-term fluctuations in salinity of the water. Udden (1924, pp. 351–52) speculated on the length of time represented by individual laminae and by groups of laminae. He tentatively concluded (1924, p. 352) that the individual laminae represented annual cycles and suggested correlation with sunspot cycles for groups of laminae. These seem to be reasonable interpretations as to time represented, and could be caused by changes in salinity due to variations in temperature, evaporation, sea-level, or wind. Adams (1944, p. 1605) also notes the presence of thin laminae of similar type in many of the limestones associated with evaporites. These laminae perhaps also may be the results of annual fluctuations of salinity.

The validity of the concepts is favored by the good agreement between many evaporite sections described in the literature and the sequence which can be predicted from oceanographic and chemical data and theoretical consideration without recourse to changes in channel restriction. Testing of the inferred process by comparison of hypothetical and actual sequences shows that observed variations can be explained on the basis of changing equilibrium relationships within the basin. In many instances these environmental changes seem to provide the most satisfactory explanation. Such a treatment tacitly excludes from consideration vertical structural movements or periodic closing of the channel. Many variations in described sections, however, have been interpreted to be the results of tectonic movements or channel closures which assume environmental uniformity. These mechanisms also are capable of producing the same types of changes in equilibrium conditions by relaxing or increasing physical restriction to flow in the channel. At any given time deposition of evaporites requires a suitable basin within which the processes that have been described can act. Changes of physical character in the basin or its environs, in the evaporation-precipitation budget, or in channel characteristics produce related changes in equilibrium conditions and in the material being deposited. Detailed reconstruction of evaporation and structural history within a particular basin requires equally detailed examination of the rocks in order to detect past fluctuations of salinity conditions and to interpret their causes.

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[3] It is not implied that all limestones in a sequence containing evaporites are produced by precipitation from a concentrated solution, since freshening, even below normal marine salinities, may occur during fluctuations in excess of evaporation over precipitation plus runoff.

## CONCLUSIONS

1. Evaporites are deposited in restricted arms of the sea in areas where evaporation exceeds precipitation and runoff. Large basins, remote from the open sea, are most satisfactory.
2. Circulation in the basin is established similar to that found in modern estuaries, so that a continuous inflowing surface current of partly concentrated solution is counterbalanced in part by a continuous return flow at depth of concentrated brine toward the sea.
3. The salinity achieved by evaporation of surface water represents an equilibrium between evaporation, precipitation plus runoff, and flow from and to the sea. High salinity is developed because of restriction to brine escape. That brine which does escape when equilibrium conditions are established returns to the sea those salts which have not been precipitated.
4. Restrictions to escape of the deep brine are in part static (as physical barriers) and in part dynamic (as relationship between pressures due to hydrostatic head and density distribution, friction between currents flowing in opposite directions, and friction between the deep current and the channel bottom). The basin equilibrium is dynamic and is principally sensitive to fluctuations of excessive evaporation and degree of channel restriction.
5. Horizontal segregations of pure evaporite deposits are produced because of the development of a strong horizontal salinity gradient, salinities increasing from the entrance to the head of the evaporating pan, and by the different salinity ranges at which precipitation of different salts occurs.
6. The vertical sequence of beds which result from salinity changes can be predicted approximately from experiments on evaporation of sea water. The predicted sequence results from lateral migration of the horizontal salinity gradient and shows excellent agreement with natural sequences which have been described in detail. Salinity changes are produced principally by changes in precipitation or channel restriction and to lesser extent by variations of temperature, sea-level, or wind stress.
7. Extreme fluctuations in the precipitation-evaporation budget, so that precipitation and runoff are predominant, can result in a change from conditions of an oxygenated evaporation pan to conditions of an euxinic basin within the same physical framework.

## REFERENCES

ADAMS, J. E., 1944, "Upper Permian Ochoa Series of Delaware Basin, West Texas and Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 28, No. 11 (November), pp. 1596–1625.

ADAMS, J. E., AND FRENZEL, H. N., 1950, "Capitan Barrier Reef, Texas and New Mexico," *Jour. Geol.*, Vol. 58, pp. 289–312.

BAKER, A. A., DANE, C. H., AND REESIDE, J. B., JR., 1933, "Paradox Formation of Eastern Utah and Western Colorado," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, pp. 963–80.

BARTON, D. C., 1925a, "The Salt Domes of South Texas," *ibid.*, Vol. 9, pp. 536–89.

———, 1925b, "The American Salt Dome Problems in the Light of the Roumanian and German Salt Domes," *ibid.*, pp. 1227–68.

BRANSON, E. B., 1915, "Origin of Thick Gypsum and Salt Deposits," *Bull. Geol. Soc. America*, Vol. 26, pp. 231–42.

BROWN, L. S., 1931, "Cap Rock Petrography," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, pp. 509–30.

———, 1934, "Age of Gulf Border Salt Deposits," *ibid.*, Vol. 18, pp. 1227–96.

CLARKE, F. W., 1924, "The Data of Geochemistry," *U. S. Geol. Survey Bull. 770.* 841 pp.

COLLIER, A., AND HEDGPETH, J. W., 1950, "An Introduction to the Hydrography of Tidal Waters of Texas," *Pub. Inst. Marine Sci.*, Vol. 1, No. 2, pp. 121–94.

EWING, G. C., 1950, "A Survey of San Diego Bay," *U.S.N.R. Research Unit 11-5 Mimeogr. Rept.* (December 31). 21 pp., 9 figs., 3 appendices.

FLEMING, R. H., AND REVELLE, R. R., 1939, "Physical Processes in the Ocean," *Recent Marine Sediments*, Amer. Assoc. Petrol. Geol., pp. 48–141.

HEDGPETH, J. W., 1953, "Introduction to the Biogeography of the Northern Gulf of Mexico," *Pub. Inst. Marine Sci.* (in press).

HILL, A. E., 1937, "The Transition Temperature of Gypsum to Anhydrite," *Jour. Amer. Chem. Soc.*, Vol. 59, Pt. 2, pp. 2242–44.

HILLS, J. M., 1942, "Rhythm in Permian Seas—A Paleogeographic Study," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, pp. 217–55.

JUDSON, S., 1952, "Arroyos," *Sci. American*, Vol. 187, No. 6, pp. 71–76.

KETCHUM, B. H., 1951, "The Exchanges of Fresh and Salt Waters in Tidal Estuaries," *Jour. Marine Res.*, Vol. 10, pp. 18–38.

KING, P. B., 1942, "Permian of West Texas and Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, pp. 535–763.

KING, R. H., 1947, "Sedimentation in Permian Castile Sea," *ibid.*, Vol. 31, pp. 470–77.

KROENLEIN, G. A., 1939, "Salt, Potash, and Anhydrite in Castile Formation of Southeast New Mexico," *ibid.*, Vol. 23, pp. 1682–93.

KRUMBEIN, W. C., 1951, "Occurrence and Lithologic Associations of Evaporites in the United States," *Jour. Sed. Petrology*, Vol. 21, pp. 63–81.

LANG, W. B., 1937, "The Permian Formations of the Pecos Valley of New Mexico and Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 21, pp. 833–98.

MUIR, J. L., 1934, "Anhydrite-Gypsum Problem of Blaine Formation, Oklahoma," *ibid.*, Vol. 18, pp. 1297–1312.

OCHSENIUS, C., 1888, "On the Formation of Rock-Salt Beds and Mother Liquor Salts," *Proc. Acad. Nat. Sci. Philadelphia*, Vol. 40, pp. 181–87.

PHALEN, W. C., 1919, "Salt Resources of the United States," *U. S. Geol. Survey Bull. 669.* 284 pp.

POSNJAK, E., 1938, "The System $CaSO_4$—$H_2O$," *Amer. Jour. Sci.*, Vol. 35A, pp. 247–72.

PRITCHARD, D. W., 1950, "Notes on the Dynamics of Estuarine Waters," *Proc. Colloquium on Flushing of Estuaries*, Woods Hole Oceanographic Inst., Ref. No. 50-37, pp. 49–60.

———, 1951, "The Physical Structure, Circulation, and Mixing in a Coastal Plain Estuary," *unpublished doctor's dissertation*, Univ. of California, Scripps Institution of Oceanography. 60 pp.

REDFIELD, A. C., 1950, "Note on the Circulation of a Deep Estuary—The Juan de Fuca-Georgia Straits," *Proc. Colloquium on Flushing of Estuaries*, Woods Hole Oceanographic Inst., Ref. No. 50-37, pp. 175–77.

RHODES, R. F., 1950, "Effect of Salinity on Current Velocities, Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena," *Comm. on Tidal Hydraulics, Corps of Engineers, U. S. Army, Rept. 1.*

ROTH, R. I., 1942, "West Texas Barred Basin," *Bull. Geol. Soc. America*, Vol. 53, pp. 1659–74.

RUSSELL, R. J., 1936, "Physiography of Lower Mississippi River Delta," *Louisiana Geol. Survey Geol. Bull. 8.* 199 pp.

SCHALLER, W. T., AND HENDERSON, E. P., 1932, "Mineralogy of Drill Cores from the Potash Field of New Mexico and Texas," *U. S. Geol. Survey Bull. 833.* 124 pp.

SIMMONS, H. B., 1952, "Salinity Problems," *Proc. Second Conference on Coastal Engineering* (Houston, Texas, November, 1951), pp. 68–85.

STEWART, F. H., 1951a, "The Petrology of the Evaporites of the Eskdale No. 2 Boring, East Yorkshire, Part II, The Middle Evaporite Bed," *Mineralogical Magazine*, Vol. 29, pp. 445–75.

———, 1951b, "The Petrology of the Evaporites of the Eskdale No. 2 Boring, East Yorkshire, Part III, The Upper Evaporite Bed," *ibid.*, pp. 557–72.

STOMMEL, H., AND FARMER, H. G., 1952a, "On the Nature of Estuarine Circulation," *Woods Hole Oceanographic Inst. Tech. Rept. 52-51* (Pt. I, Chapts. I and II).

——— AND ———, 1952b, "On the Nature of Estuarine Circulation," *ibid.*, *Tech. Rept. 52-63* (Pt. III, Chapt. VII).

STONE, R. W., AND OTHERS, 1920, "Gypsum Deposits of the United States," *U. S. Geol. Survey Bull. 697*. 326 pp.

SVERDRUP, H. U., JOHNSON, M. W., AND FLEMING, R. H., 1946, *The Oceans, Their Physics, Chemistry, and General Biology*. 1087 pp. Prentice-Hall, New York.

TULLY, J. P., 1937, "Oceanography of Nootka Sound," *Jour. Biol. Board Canada*, Vol. 3, pp. 43–69.

———, 1949, "Oceanography and Prediction of Pulp Mill Pollution in Alberni Inlet," *Bull. Fish. Res. Board Canada*. 169 pp.

UDDEN, J. A., 1924, "Laminated Anhydrite in Texas," *Bull. Geol. Soc. America*, Vol. 35, pp. 347–54.

ZENKEVICH, L. A., 1947, "Fauna and Biological Productivity of the Sea," *Soviet Science*, Tome II, pp. 393–99.

JOURNAL OF PALEONTOLOGY, VOL. 27, NO. 6, PP. 805–813, PLS. 84–85, 1 TEXT FIG., NOVEMBER 1953

# MESOZOIC AND LATE TERTIARY RADIOLARIA OF ROTTI

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ABSTRACT—Re-examination of the radiolarian fauna described by Tan Sin Hok from the island of Rotti, near Timor, and considered by him to be probably Pliocene, reveals the presence of saturnalids and other microfossils indicating a Mesozoic age. Another sample, collected by the First Netherlands Timor Expedition from a nearby locality, contains a radiolarian fauna which is probably Pliocene or Pleistocene in age. Twenty-five species and subspecies, six of which are new, are determined in this latter fauna, which is in some respect similar both to that of the adjacent seas of the present day and to various late Tertiary faunas previously described from Europe and North America.

## INTRODUCTION

ALTHOUGH the Radiolaria are at present seldom used as time-indicators in stratigraphic work, it appears probable that in the future they will prove to be very useful for this purpose. It is well known that the group in general possesses two of the main characteristics necessary for good index fossils: being planktonic, they are ubiquitous in the oceans of the present day, and have apparently been so since the Paleozoic, and secondly, their siliceous skeletons are readily preserved in fine-grained marine sediments. Also, there is already a large amount of evidence in the literature to indicate that the radiolarian faunas of the major geological periods differed considerably from one another, thus providing the third necessary characteristic for a group of index fossils—short time-ranges. However, many more radiolarian assemblages must be described from sediments of various ages before it will be possible to use these fossils for accurate age determinations.

A survey of the literature on late Tertiary radiolarian faunas shows that the Miocene assemblages described from North American and European localities have certain characteristics in common, and are transitional between the early Tertiary and Recent faunas. But there is one East Indian assemblage, described as being late Tertiary in age, which does not fit into this general picture: it differs in many respects from other late Tertiary faunas, and is in fact similar to Mesozoic faunas described from many localities throughout the world. The author has re-examined sediments from this East Indian locality with the object of determining the reason for this apparent anomaly.

The fauna in question is that described by Tan Sin Hok (1927) from four samples of calcareous sediment collected near Bebalain, on the island of Rotti, near Timor. Three of these samples (Series 8, Nos. 149, 150 and 154) were collected by the First Netherlands Timor Expedition (1910–1912) under the leadership of Dr. G. A. F. Molengraaf, and the fourth (No. 384) was collected by Dr. R. D. M. Verbeek in 1898–99. Tan Sin Hok (1927, p. 9, footnote) considered this fauna to be "Young" Tertiary in age, probably Pliocene, and subsequent authors have in general followed this determination. However, Brouwer (1922, p. 74) had indicated that some of these samples (Nos. 149, 150 and 154) might be at least partly Mesozoic in age, and Tan Sin Hok's determination of a "Young Tertiary" age was never substantiated by convincing evidence.

The age of the fauna described from these four samples is of considerable importance, as it is the only radiolarian assemblage originally ascribed to the later Tertiary which has been described from the East Indian region. Through the courtesy of Dr. H. A. Brouwer, of the Geological Institute of the University of Amsterdam, and Prof. H. J. de Wijs, of the Instituut voor Mijnbouwkunde at Delft, the author has been able to examine some of the samples from the First Netherlands Timor Expedition, which are stored at the latter institute.

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[1] Contribution from the Scripps Institution of Oceanography, new series, no. 654.

The samples Nos. 149, 150 and 154 were examined, in order to see if any further indication of their age could be found. Nothing was observed to contradict the previous opinion of the present author (1952, p. 10) that this fauna is Mesozoic in age. In fact, this impression was strengthened by the finding of fragments of *Spongosaturnalis* and perhaps *Spongosaturninus*, typically Mesozoic forms which are not mentioned by Tan Sin Hok.

An examination was also made of the sample Series 8, No. 178, from near Bebalain, Rotti. Although Tan Sin Hok mentions this sample (1927, p. 17), he does not describe the Radiolaria contained. This fauna is described in some detail in the present paper, and it proves to be very late Tertiary in age, probably Pliocene or Pleistocene. In this sample, there are a few Mesozoic Radiolaria from the older formation mixed with the Tertiary forms; there can be no doubt that this is the result of reworking, and is not due to these species having persisted from the Mesozoic to the late Tertiary.

### THE MESOZOIC SAMPLES

The author (1952) has previously stated, in general terms, the reasons for suspecting the samples Nos. 149, 150 and 154 (Series 8, First Netherlands Timor Expedition) to be Mesozoic in age. A re-examination of these three samples has established the presence in each of them, of saturnalids of the types figured in Plate 84, figures 1–5.

The specimens found are all fragmentary, and it is therefore not possible to make an accurate determination of the genera or species present. It is very probable, however, that some of the specimens belong to the genus *Spongosaturnalis* Campbell and Clark. This is the case with the form figured in Plate 84, figure 2, and perhaps also Plate 84, figure 3. The thorns on the proximal ends of the spines of these specimens are disposed in such a way as to indicate that the spherical shell was spongy, and not composed of simple lattice-spheres. Also, the ring of the specimen in Plate 84, figure 2, is apparently similar to that of *Spongosaturnalis spiniferus* Campbell and Clark—it is three-sided prismatic, and bears triangular, thorn-like spines. *Spongosaturnalis* has been found only in the Upper Cretaceous of California (Campbell and Clark, 1944b).

The specimen figured in Plate 84, figure 1, may belong to the genus *Spongosaturninus* Campbell and Clark, which also has been recorded only from the Upper Cretaceous of California. The thorns on the proximal end of the spine are arranged in seven transverse rows, and although this may indicate that a similar number of concentric spheres was present, it is not impossible that the sphere was partly or wholly composed of a spongy framework. The ring does not have the form of any of Campbell and Clark's species, *Spongosaturninus ellipticus*, *S. latuformis* and *S. parvulus*, but it has a striking similarity to the form described as *Saturnalis polymorphus* by Squinabol (1914, p. 293), this latter form having been found in the Jurassic of Cittiglio (Laveno), and the Cretaceous of Novale (Vicentino), Baone (Euganei), and Couldson (Surrey).

The fragments figured in Plate 84, figures 4 and 5, cannot be determined accurately, but they may be compared with the rings of *Saturnalis lateralis* (Upper Cretaceous of California, Campbell and Clark, 1944b), *S. dicranacanthos* (Italian Liassic, Jurassic and Cretaceous, Squinabol, 1914) and *S. variabilis* (Jurassic of Cittiglio, Squinabol, 1914).

Although these forms are not sufficient to give a closer indication of the age of the fauna, they are strong evidence for a Mesozoic age.

Associated with the chalky sample No. 150, is a piece of chert, which on sectioning shows, besides the Cyrtoidea present in the chalk, numerous bodies (text fig. 1) similar to those described by Davis (1950, p. 211) as *Meyenella meyeni*. Fossils of this type have been found in hard rocks from the Devonian to the Upper Cretaceous, and ac-

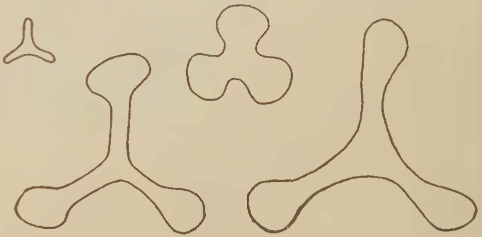

FIG. *1*—"*Meyenella*"-like bodies observed in a thin-section of the chert sample No. 150. ×320.

cording to Davis they are most abundant in the Jurassic. At least in the present case, however, they are probably transverse and oblique sections of three-bladed prismatic spines, which occur in great numbers in the associated chalky sample. Tan Sin Hok (1927, p. 33) mentioned the abundance of such spines in the sediments which he examined, and assigned them to the Sphaeroidea.

### THE LATE TERTIARY FAUNA

In pronounced contrast to the Mesozoic samples discussed above, most of the Radiolaria present in sample No. 178 are very similar to the forms at present living in the tropical oceans. That is, with the exception of some Mesozoic forms (such as *Stylosphaera squinaboli* Tan Sin Hok, *Tricolocapsa frequens* Tan Sin Hok, *Stichomitra pseudoscalaria* Tan Sin Hok, *Dictyophimus gracilis* Tan Sin Hok, etc.) which have obviously been reworked, and redeposited with the Tertiary forms as an heterochthonous element of the fauna. In the subsequent description of the fauna, these reworked forms will be ignored, but it is of interest to note their presence, as this is another example of the development of mixed micro-faunas, which are being recognized in an increasing number of instances.

The late Tertiary fauna of Rotti can be dated approximately by comparison with previously described Miocene and Pliocene faunas on the one hand, and the Recent fauna on the other. The absence or scarcity of any species closely corresponding to the widespread Miocene type represented by *Eucyrtidium delmontense* Campbell and Clark, and *Stichocorys saccoi* Vinassa, indicates that if the Rotti fauna is late Tertiary, it is probably post-upper Miocene. The presence and abundance of such forms as *Tetrapyle quadriloba* and *Larcospira quadrangula*, which are common in the tropical oceans of the present day, indicate an age not older than late Miocene. And the assemblage is distinguished from that of Recent tropical seas by the absence of such forms as *Euchitonia elegans*, *Panartus quadrijugus*, *Spongaster tetras*, and *Pterocanium tricolpum*, which, so far as our knowledge goes, are at present ubiquitous in the warm oceans (Riedel, 1952, pp. 11, 12). The stratigraphic significance of each of the forms present will be discussed in the systematic section below.

There is only one previous description of Pliocene Radiolaria, and this is the fauna described by Seguenza (1880) from the province of Reggio (Calabria). Unfortunately, Seguenza's species descriptions are often inadequate for identification of the forms, and there are no figures of the species which he found. Therefore, it is difficult to compare his fauna with that from Rotti, but nevertheless it is possible to trace some significant similarities between the two. For example, Seguenza's fauna includes two species of *Tetrapyle*, one of them *Tetrapyle* cf. *T. quadriloba* (Ehrenberg), which is the form occurring on Rotti; and one of the two species of *Pterocanium* which Seguenza describes from his material is apparently not very different from a species described in this paper.

The systematic description of the fauna from sample No. 178 (First Netherlands Timor Expedition), which follows, includes only the more common of the forms present. Species represented in the available material by only a few specimens are generally omitted, as it is usually necessary to have a considerable number to indicate the range of variation, and typical form of a species. The system of classification used is that of Haeckel (1887). The figures were drawn with the help of a camera lucida, and have been reduced during reproduction to one-third of their original size. Types and figured specimens will be stored in the collections of the U. S. National Museum, Washington, D.C.

### SYSTEMATIC DESCRIPTION

#### Genus ACROSPHAERA Haeckel

#### ? ACROSPHAERA INFLATA Haeckel

Plate 84, figure 10

*Acrosphaera inflata* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 101, pl. 5, fig. 7.

There are a considerable number of specimens, mostly broken, which correspond with Haeckel's description except that the spines are longer (up to 60 $\mu$). Because of this fact, and as it is impossible to determine whether these tests belonged to colonial Radiolaria, they are doubtfully assigned to this species. Haeckel described the species from a surface sample from the North Atlantic.

### ? ACROSPHAERA sp.
Plate 84, figure 9

Shell thin-walled, spherical, with 15–25 short conical, often oblique spines arising from small, perforated, conical elevations of the shell surface. On the half equator are 8–15 subcircular pores of very varying diameter, 0.3–5 times as broad as the wide flat intervening bars.

Diameter of shell 75–110 $\mu$; of the pores 4–22 $\mu$. Length of the spines (including conical bases ) 10–20 $\mu$.

Tests of this species are rather common in the Rotti sediment, but, owing to their isolation, it is not possible to determine whether or not they belonged to a colonial radiolarian.

### Genus SOLENOSPHAERA Haeckel
### ? SOLENOSPHAERA VARIABILIS Haeckel
Plate 84, figure 8

*Tetrasolenia quadrata* EHRENBERG, 1873, Abhandlungen der königlich Akademie der Wissenschaften zu Berlin, 1872, pl. 10, fig. 20.
*Solenosphaera variabilis* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 113.

In the assemblage were found a few specimens of a form which corresponds to Ehrenberg's figure and Haeckel's description, except that the shells are generally smaller, and the porous tubuli are relatively longer and narrower.

The species has been recorded from the Indian Ocean between Zanzibar and the Comoro Islands, and from the central tropical Pacific.

### Genus OTOSPHAERA Haeckel
### OTOSPHAERA POLYMORPHA Haeckel

*Otosphaera polymorpha* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 116, pl. 7, fig. 6.

Isolated shells correspond well with Haeckel's description, and it appears probable that they belong to this colonial species. The species was described from the surface of the Indian Ocean.

### Genus HEXALONCHE Haeckel
### HEXALONCHE PHAENAXONIA Haeckel

*Hexalonche phaenaxonia* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 180.

The forms present in the sediment from Rotti correspond well with the original description. Haeckel recorded the species from the central Pacific, presumably in Recent sediments.

### Genus SPONGOCORE Haeckel
### SPONGOCORE PUER Campbell and Clark

*Spongocore* (*Spongocorissa*) *puer* CAMPBELL and CLARK, 1944, Geol. Soc. America, Spec. Paper No. 51, p. 22, pl. 3, figs. 7–9.

Specimens of this species correspond well with the original description. The species has been recorded from the Delmontian of southern California.

### Genus CYPHONIUM Haeckel
### CYPHONIUM FACETTARIUM Haeckel

*Cyphonium facettarium* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 365.

The specimens in the assemblage correspond well with Haeckel's description. This species has previously been recorded only from the western tropical Pacific.

### Genus PANARTUS Haeckel
### PANARTUS AVITUS Riedel, n. sp.
Plate 84, figure 7

Four chambers of the cortical shell of

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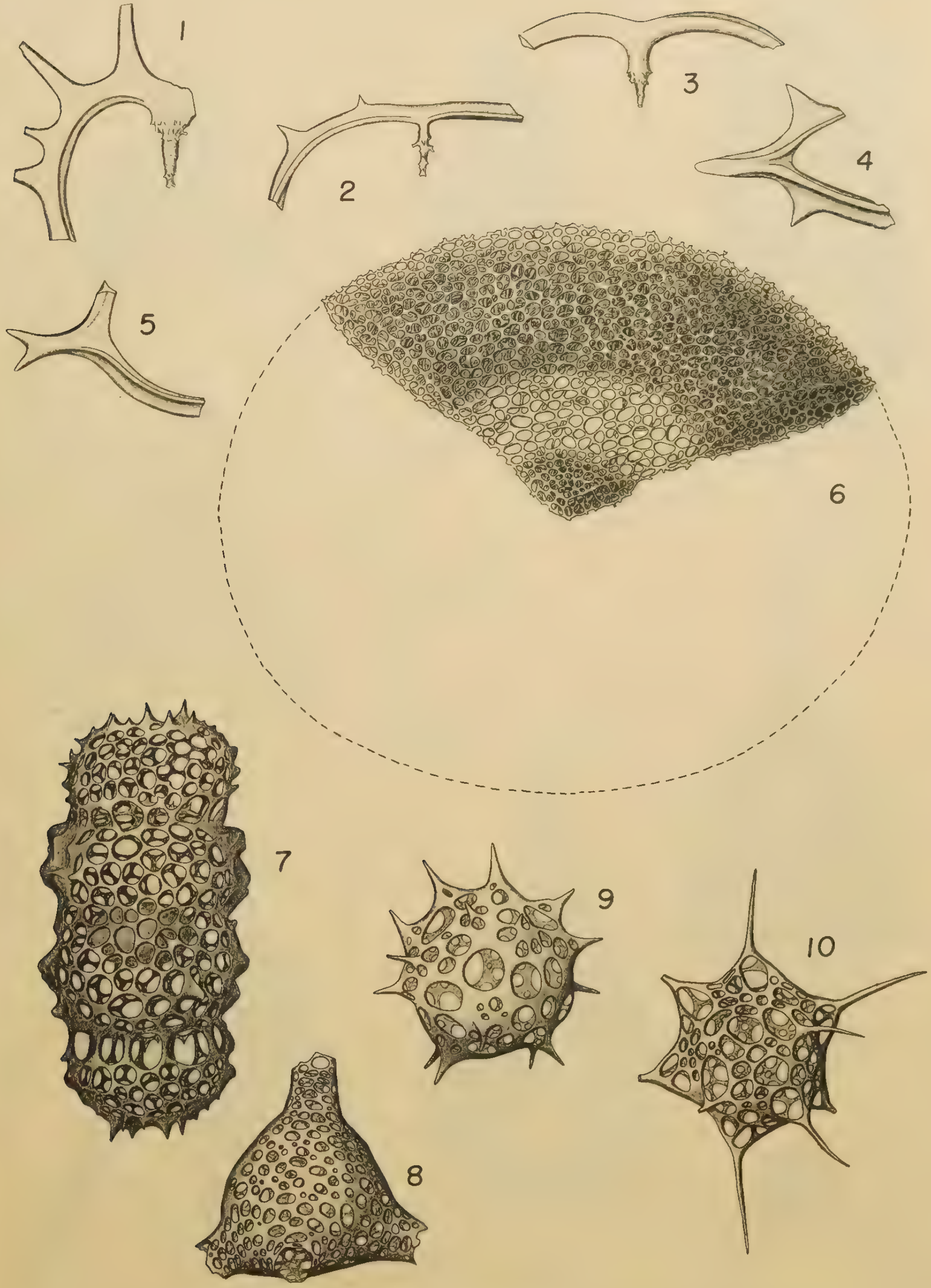
### EXPLANATION OF PLATE 84

FIG. *1—? Spongosaturninus* sp., ×150. A fragment of the ring and radial spine. (p. 860)
*2, 3—? Spongosaturnalis* sp., ×150. Fragments of the ring and radial spines. (p. 806)
*4, 5—? Saturnalis* spp., ×150. Fragments of the rings with their accessory spines. (p. 806)
*6—Spongodiscus communis fragilis* Riedel, n. subsp. Holotype, ×350. Oblique view. Only a portion of the disc is drawn in detail, the outline of the remainder being indicated by the broken line. (p. 809)
*7—Panartus avitus* Riedel, n. sp. Holotype, ×370. (p. 808)
*8—? Solenosphaera variabilis* Haeckel, ×320. (p. 808)
*9—? Acrosphaera* sp. ×320. (p. 808)
*10—? Acrosphaera inflata* Haeckel, ×260. (p. 807)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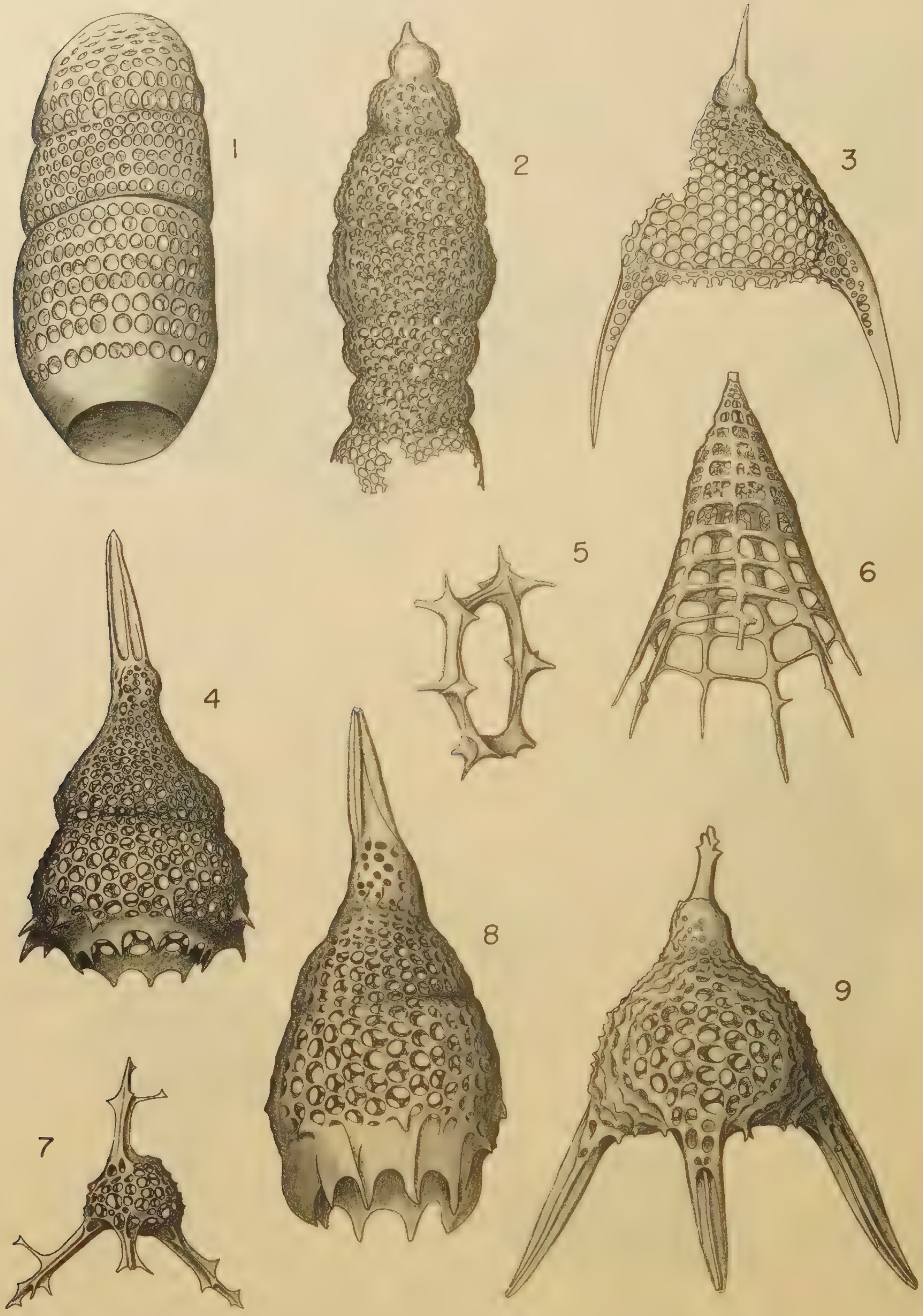
Riedel, Mesozoic and late Tertiary Radiolaria of Rotti



Riedel, Mesozoic and late Tertiary Radiolaria of Rotti similar general form, kidney-shaped (as in *Panartus tetrathalamus* Haeckel), except that the two distal chambers are somewhat smaller than the proximal pair. Pores of the proximal chambers subcircular, 3–6 times as broad as the intervening bars, 13–15 on a half equator, 7–9 on the length of a chamber. Walls of the proximal chambers bearing large, obtuse protuberances, 1.5–2 times as broad as the pores and half as long, usually concentrated on the widest part of the chambers. Pores of the distal chambers similar to those of the proximal, except for a row of larger pores at the junction with the latter. Surface of the distal chambers usually covered with short, acute, conical spines, approximately as long as the diameter of the pores. External medullary shell compressed, its greatest diameter half the equatorial diameter of the cortical shell; the inner medullary shell not clearly visible.

Total length of the shell 162–180 $\mu$; of the apical spines 2–6 $\mu$. Maximum breadth of the proximal cortical chambers 80–85 $\mu$; of the distal cortical chambers 65–75 $\mu$; of the equatorial constriction 70–75 $\mu$; of the external medullary shell 32–35 $\mu$.

This species differs from all others of the genus in the heavy protuberances on the proximal chambers of the cortical shell. Apart from this character, it corresponds closely to the cosmopolitan Recent species *Panartus tetrathalamus* Haeckel and *P. quadrijugus* Haeckel. There is also considerable similarity to *P. tetrameres* Haeckel from the late Tertiary of Caltanisetta, Sicily.

### Genus HELIODISCUS Haeckel

### HELIODISCUS ASTERISCUS Haeckel

*Heliodiscus asteriscus* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 445, pl. 33, fig. 8.

Specimens occurring in the sediment from Rotti are quite typical. According to Haeckel, this species is cosmopolitan in the oceans of the present day.

### Genus SPONGODISCUS Ehrenberg

### SPONGODISCUS COMMUNIS Clark and Campbell FRAGILIS Riedel, n. subsp.

Plate 84, figure 6

Discoidal shell large, circular, with plain margin; thickened in the central portion and the outer region, with a thinner zone, composed of but one or two layers of meshes, between these thicker zones. Framework irregular, with five or six concentric annular rings in the central area; meshes everywhere irregularly polygonal, 3–5 times as broad as the bars. Diameter of the disc 250–300 $\mu$; of the pores 4–10 $\mu$.

This subspecies differs from the typical form (Clark and Campbell, 1942, p. 47, from the Eocene of Mt. Diablo, California) in that the thinner zone of the shell is more delicate, and the concentric rings of the central region are generally better defined.

### Genus TETRAPYLE Müller

### TETRAPYLE QUADRILOBA (Ehrenberg)

*Schizomma quadrilobum* EHRENBERG, 1860, Monatsberichten der königlich preussischen Akademie der Wissenschaften zu Berlin, p. 815.

*Tetrapyle quadriloba* (Ehrenberg) HAECKEL, 1862, Monogr. d. Radiolarien, Berlin, p. 436.

This species is very common in the fauna from Rotti, and this fact is one of the strongest indications for a Pliocene or Pleistocene age of the fauna. *Tetrapyle quadriloba* is one of the most abundant Radiolaria in the seas of the present day, and it must have risen to this ascendancy during the latest Tertiary or early Quaternary. The only fossil records of the species are in the Pliocene of

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EXPLANATION OF PLATE 85

FIG. *1*—*Tricolocampe* (?) *polyzona* Haeckel, ×530. (p. 812)
*2*—*Eucyrtidium elongatum peregrinum* Riedel, n. subsp. Holotype, ×320. (p. 812)
*3*—*Pterocanium* sp., ×260. A shell with one foot and part of the thorax broken away, illustrating the general form, the nature of the feet, and the radial ribs in the thoracic wall. (p. 811)
*4*—*Lamprocyclas maritalis antiqua* Riedel, n. subsp. Holotype, ×260. (p. 811)
*5*—*Zygocircus triquetrus* Haeckel, viewed obliquely. ×320. (p. 810)
*6*—? *Bathropyramis woodringi* Campbell and Clark, ×150. (p. 810)
*7*—*Tripilidium cladopodium exiguum* Riedel, n. subsp. Holotype, ×320. (p. 810)
*8*—*Calocyclas margatensis* Campbell and Clark, ×260. (p. 811)
*9*—*Lychnodictyum audax* Riedel, n. sp. Holotype, ×260. (p. 810)

Calabria (Seguenza, 1880, p. 231) and in the Tortonian of Sicily (Stöhr, 1880, p. 89).

### Genus Larcospira Haeckel

### Larcospira quadrangula Haeckel

*Larcospira quadrangula* Haeckel, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 696, pl. 49, fig. 3.

Specimens of this species in the sediment from Rotti are quite typical. The species was originally described from the central Pacific, apparently from Recent sediments.

### Genus Zygocircus Bütschli

### Zygocircus triquetrus Haeckel

Plate 85, figure 5

*Zygocircus triquetrus* Haeckel, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 947, pl. 81, fig. 3.

The sediment from Rotti contains typical examples of this species, which Haeckel records as being cosmopolitan in the surface waters of the present oceans. It has not previously been recorded from fossil assemblages.

### Genus Eucoronis Haeckel

### Eucoronis angulata Haeckel

*Eucoronis angulata* Haeckel, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 978, pl. 82, fig. 3.

Typical specimens of this species occur in the fauna. The form was described by Haeckel from the central Pacific, presumably from Recent sediments.

### Eucoronis nephrospyris Haeckel

*Eucoronis nephrospyris* Haeckel, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 977, pl. 82, fig. 5.

The specimens occurring in the sediment from Rotti are quite typical. This species is cosmopolitan in the oceans of the present day, and has not previously been found fossilized.

### Genus Tripilidium Haeckel

### Tripilidium cladopodium Haeckel exiguum Riedel, n. subsp.

Plate 85, figure 7

Shell approximately hemispherical, with rough surface, having 60–70 pores of varying sizes, 1.5–6 times as broad as the thin intervening bars. Apical horn three-bladed, acute, bearing few simple or branched secondary spines which arise from the blades in the distal half of the spine. Three strongly divergent feet arising from the base of the shell, of approximately the same length as the apical horn, and resembling it in shape, bearing 4–7 simple or branched secondary spines. Mouth somewhat constricted.

Height of the shell 32–40 $\mu$; breadth 45–52 $\mu$. Length of the apical horn 40–65 $\mu$; of the basal feet 40–55 $\mu$.

This subspecies is similar in form to Haeckel's species but it is constantly smaller, and the pores are larger in relation to the intervening bars. Haeckel records the species from the central Pacific, presumably from Recent sediments.

### Genus Bathropyramis Haeckel

### ? Bathropyramis woodringi Campbell and Clark

Plate 85, figure 6

*Bathropyramis woodringi* Campbell and Clark, 1944, Geol. Soc. America, Spec. Paper No. 51, p. 39, pl. 5, fig. 21, 22.

Specimens which are tentatively assigned to this species are not uncommon in the assemblage. None of the examples observed is complete at the apex, and thus it is not possible to determine definitely whether the form possesses a separate cephalis or apical spine: however, it seems probable that neither of these were present in the entire skeleton, as the broken edge of the apex indicates that it is composed of a simple, thin-walled cap. The specimens described by Campbell and Clark have eight radial beams, whereas those in the Rotti fauna have either eight, or more commonly, nine. In other respects, the present specimens correspond well with the type examples.

The only previous record of this species is from the Malaga mudstone (Delmontian) of southern California.

### Genus Lychnodictyum Haeckel

### Lychnodictyum audax Riedel, n. sp.

Plate 85, figure 9

Shell campanulate, with rough surface and distinct collar stricture. Length of the two joints 1:4, breadth 1:5. Cephalis subspherical, with rather few, subcircular, well-separated pores, bearing a conical horn of the same to twice the length, which has short, obtusely conical protuberances in its distal portion. Thorax subglobular, with rough ridges between the large rounded pores, which are 2–5 times as broad as the intervening bars. Peristome constricted, the feet arising slightly above the margin. Feet of approximately the same length as the thorax, triangular pyramidal with pronounced blades, fenestrated in the proximal portion, almost straight, divergent. Small spines are often present on the lower edge of the thorax, as if remnants from a reduced abdomen.

Length of the apical horn 35–50 $\mu$; of the cephalis 24–28 $\mu$; of the thorax 90–105 $\mu$; of the feet 75–110 $\mu$. Breadth of the cephalis 25–30 $\mu$; of the thorax 110–130 $\mu$; of the thoracic pores 4–12 $\mu$.

This species differs from all others of the genus in the nature of the apical horn, and in the globular thorax with constricted peristome. It is perhaps most closely related to living species such as *L. sethopodium* Haeckel and *L. wyvillei* Haeckel, which have been recorded from the south Atlantic and central Pacific, respectively.

### Genus PTEROCANIUM Ehrenberg

### PTEROCANIUM PRAETEXTUM (Ehrenberg)

*Lychnocanium praetextum* EHRENBERG, 1873, Abhandlungen der königlich Akademie der Wissenschaften zu Berlin, 1872, p. 297, pl. 10, fig. 2.

*Pterocanium praetextum* (Ehrenberg) HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 1330.

Specimens of this species occurring in the fauna are quite typical. The species was described by Ehrenberg from the bottom sediment between Zanzibar and the Comoro Islands, and was found by Haeckel off Ceylon, and by Cleve (1904) in the Arabian Sea.

### PTEROCANIUM sp.

Plate 85, figure 3

As only fragments of this rather delicate species were found, a full description cannot be given.

The cephalis is small, spherical with few well-separated pores, and bears a conical horn of approximately twice the length. The thorax is probably almost pyramidal, with circular pores, regularly disposed, 3–5 times as broad as the narrow intervening bars. The radial ribs in the thorax are well defined as solid rods, but are not raised above the shell surface. The feet are approximately as long as the thorax, divergent, proximally fenestrated, with convex back. Only traces of the abdomen are preserved, but it appears that it cannot have been long (perhaps 0.25 as long as the thorax). Total length of the figured specimen 250 $\mu$.

This form is of interest stratigraphically, for although species resembling it are common in the seas of the present day (*Pterocanium eucolpum* Haeckel and *P. trilobum* Haeckel), they have not been found fossilized except in the Pliocene of Calabria (*P. diceras* Seguenza, 1880).

### Genus CALOCYCLAS Ehrenberg

### CALOCYCLAS MARGATENSIS Campbell and Clark

Plate 85, figure 8

*Calocyclas margatensis* CAMPBELL and CLARK, 1944, Geol. Soc. America, Spec. Paper No. 51, p. 47, pl. 6, figs. 17, 18.

The examples of this species in the fauna vary a little from the description given by Campbell and Clark, but these differences are not of sufficient magnitude or constancy to justify the erection of a new species or subspecies. In some specimens (pl. 85, fig. 8) the peristomial region is heavily silicified, in contrast to the thin wall of the distal part of the abdomen described by Campbell and Clark. Also, small thorns are often developed on the lower part of the abdomen; this may also be the case in the specimen figured by Campbell and Clark on their plate 6, figure 17, although it is not mentioned in the text.

This species has previously been recorded from the Miocene of California, and from a late Tertiary western Pacific sediment (Riedel, 1952).

### Genus LAMPROCYCLAS Haeckel

### LAMPROCYCLAS MARITALIS Haeckel ANTIQUA Riedel, n. subsp.

Plate 85, figure 4

Shell a little rough, campanulate, with indistinct collar, but pronounced lumbar stricture. Approximate proportions of the lengths of the segments 2:5:5; their breadths 1:4:5. Cephalis spherical, with about 25 well-separated circular pores, and bearing a thick three- or four-edged apical spine almost half as long as the shell. Thorax conical in the apical section, inflated below, having closely-spaced circular pores 3–4 times as broad as the intervening bars: 12–15 pores on a half equator in the widest part of the thorax, and a similar number in a vertical series. Abdomen slightly inflated, its pores 1.5–2 times as large as those of the thorax, bearing the same relation to the intervening bars as those of the latter, and arranged in indefinite vertical series of 6–8 pores each. Outer coronal of the peristome not well-developed, consisting of 8–15 thorns arising from the abdomen above, or in the upper portion of, the peristomial lamella. Inner coronal with 9–11 somewhat convergent triangular teeth, arising from the lower edge of the peristomial lamella, which is approximately as wide as an abdominal pore.

Length of the horn 65–70 $\mu$; of the cephalis 24–26 $\mu$; of the thorax 60–65 $\mu$; of the abdomen 60–70 $\mu$; of the peristomial teeth 5–10 $\mu$. Breadth of the cephalis 24–26 $\mu$; of the thorax 95–105 $\mu$; of the abdomen 115–130 $\mu$.

This subspecies differs from *Lamprocyclas maritalis* Haeckel, originally described from the central Pacific, in having more pores, more closely and regularly arranged, and thinner shell-wall. Also, the thorax is more definitely campanulate; although specimens of *L. maritalis* described by Haecker (1908, pp. 455, 456) from the northern Indian Ocean approximate it in this character.

### Genus TRICOLOCAMPE Haeckel
### TRICOLOCAMPE ? POLYZONA Haeckel
Plate 85, figure 1

*Tricolocampe polyzona* HAECKEL, 1887, Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, p. 1412, pl. 66. fig. 19.

The few observed specimens of this form all had fewer rows of pores on the thorax and abdomen than indicated in the original description, but otherwise they are quite typical.

The species was found by Haeckel in the central Pacific, and "fossil in the Nicobars and in Barbados." In the sediments of the Swedish Deep Sea Expedition, it was found to be widespread in the Recent sediments of the tropical Pacific and Indian Oceans (Riedel, 1952).

### Genus LITHOMITRA Bütschli
### LITHOMITRA BRAMLETTEI Campbell and Clark

*Lithomitra* (*Lithomitrissa*) *bramlettei* CAMPBELL and CLARK, 1944, Geol. Soc. America, Spec. Paper No. 51, p. 53, pl. 7, figs. 10–14.

A few typical examples of this species were found in the assemblage. The species has previously been recorded only from the Miocene of southern California.

### Genus EUCYRTIDIUM Ehrenberg
### EUCYRTIDIUM ELONGATUM Stöhr PEREGRINUM Riedel, n. subsp.
Plate 85, figure 2

Shell with seven (or more) segments distinctly separated by constrictions, the first four segments together forming a conical section, the subsequent segments an approximately cylindrical section. Cephalis subspherical, rough, poreless, and bearing, usually eccentrically, a straight or curved conical horn of the same length. Thorax hemispherical, with rough surface, having some 40 subcircular pores, which are irregularly arranged and 1.5–3 times as broad as the intervening bars. Third segment conical, usually longer than any other, and fourth segment a cylinder bulged laterally to a greater or less degree; these two segments with rough surface, and circular pores 2–4 times as broad as the bars, often regularly arranged in indistinct vertical series, 7–9 in a vertical row on each segment, 14–20 on a half equator. Segments subsequent to the fourth are generally shorter and narrower than the third and fourth, subcylindrical, and laterally bulged: their surfaces are smooth, with irregularly disposed subcircular pores, 2–5 times as broad as the bars. The entire apertural margin of the shell was not observed, though it might be expected to be not greatly constricted, without radial apophyses.

Length of the first four segments 125–135 $\mu$; greatest breadth (in the lower part of the third segment, or the middle of the fourth) 70–80 $\mu$. Breadth of cephalis 20 $\mu$; of thorax 35–40 $\mu$; of fifth segment 60–65 $\mu$. Length of cephalis 12–15 $\mu$; of thorax 20–25 $\mu$; of third segment 35–50 μ; of fourth segment 30–40 μ; of subsequent segments 20–45 μ.

This subspecies differs from *Eucyrtidium elongatum* Stöhr (1880, p. 105, pl. 4, fig. 10) in that the pores are larger, and those on the third and fourth segments are more regularly arranged. Also, the third segment is usually conical, rather than subcylindrical.

This form is one of the more abundant in the assemblage, and has considerable stratigraphic significance. Species of *Stichocorys*, and of *Eucyrtidium* having characters tending towards *Stichocorys*, are common in the Miocene sediments of Sicily (Stöhr, 1880), Italy (Vinassa de Regny, 1900, and Luchesse, 1933), and California (Campbell and Clark, 1944a). Forms which are abundant in the upper Miocene, such as *Eucyrtidium delmontense* Campbell and Clark and *Stichocorys saccoi* Vinassa, have a conical section formed by the upper three segments, which is sharply delineated from the cylinder formed by the subsequent segments. *Eucyrtidium elongatum* Stöhr, from the Tortonian, and the subspecies here described, have four segments forming the conical section, and the break between this and the cylindrical section is not always pronounced. *Eucyrtidium elongatum peregrinum* may represent a transitional stage to a Recent form such as *Eucyrtidium cienkowskii* Haeckel.

## REFERENCES

Brouwer, H. A., 1922, Geologische onderzoekingen op het Eiland Rotti: Jaarb. v. h. Mijnwezen in Ned. Oost-Indië, Verhand. (1920), 3e ged., pp. 70–77.

Campbell, A. S., and Clark, B. L., 1944a, Miocene radiolarian faunas from southern California: Geol. Soc. America, Spec. Paper No. 51, 76 pp., 7 pls.

——, and ——, 1944b, Radiolaria from Upper Cretaceous of middle California: Geol. Soc. America, Spec. Paper No. 57, 61 pp., 8 pls.

Clark, B. L., and Campbell, A. S., 1942, Eocene radiolarian faunas from the Mt. Diablo area, California: Geol. Soc. America, Spec. Paper No. 39, 112 pp., 9 pls.

Cleve, P. T., 1904, Report on plankton collected by Mr. Thorhild Wulff during a voyage to and from Bombay: Arkiv f. Zool., K. Svenska Vetenskaps-Akad., Band 1, pp. 329–380.

Davis, A. G., 1950, The Radiolaria of the Hawasina Series of Oman: Proc., Geol. Assoc., London, vol. 61, part 3, pp. 206–217.

Haeckel, E., 1887, Report on the Radiolaria collected by H.M.S. "Challenger" during the years 1873–1876: Rept. Sci. Results H.M.S. *Challenger*, Zool., vol. 18, clxxxviii and 1803 pp., 140 pls., 1 map.

Haecker, V., 1908, Tiefsee Radiolarien. Spezieller Teil: Wissensch. Ergeb. d. Deu. Tiefsee Exped., Jena, Band 14, pp. x and 476, 85 pls.

Luchesse, C., 1933, Radiolari Miocenici di Salsomaggiore: Giornale d. Geol. Bologna (2), vol. 2 (1927), pp. 80–116, 6 pls.

Riedel, W. R., 1952, Tertiary Radiolaria in western Pacific sediments: Göteborgs Kungl. Vetensk.- o. Vitterh.- Samh. Handl., 6e följ., ser. B, Band 6, no. 3, pp. 1–18, 2 pls.

Seguenza, G., 1880, Le formazione terziarie nella provincia di Reggio (Calabria): Atti R. Accad. d. Lincei, Rome, ser. 3, Mem. Sci. Fis., 6, pp. 168–234.

Squinabol, S., 1914, Contributo alla conoscenza dei Radiolarii fossili del Veneto: Mem. Ist. Geol. d. R. Univ. di Padova, vol. 2 (1913–1914), mem. 7, pp. 249–306, 5 pls.

Stöhr, E., 1880, Die Radiolarienfauna der Tripoli von Grotte, Provinz Girgenti in Sicilien: Palaeontographica, Cassel, vol. 26, Band 2, pp. 69–124, 7 pls.

Tan Sin Hok, 1927, Over de samenstelling en het ontstaan van krijt en mergel-gesteenten van de Molukken: Jaarb. v. h. Mijnwezen in Ned. Oost-Indië, Verhand. (1926), 165 pp., 16 pls.

Vinassa de Regny, P., 1900, Radiolari Miocenici Italiani: Mem. R. Accad. Sci. d. Ist. Bologna, ser. 5, vol. 8, pp. 227–257, 3 pls.

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ALGER 1952

Section IV

# TOPOGRAPHIE SOUS-MARINE ET SÉDIMENTATION ACTUELLE

FASCICULE IV

EXTRAIT

ALGER
1953

Francis P. SHEPARD

# SUBMARINE CANYONS

## RESUME

De nombreuses vallées du fond de la mer possèdent les caractéristiques essentielles des cañons creusés sur la terre formé par des rivières. Les cañons sous-marins typiques ont des parois raides, rocheuses, des fonds étroits, un trajet à méandres et de nombreux affluents.

Plusieurs cañons ont été levés au delà du rebord continental jusqu'au fond des bassins ; mais les parties terminales sont seulement de basses vallées partiellement bordées par des *levées* naturelles.

On sait que les têtes des cañons, qui pénètrent près de la côte, reçoivent de grandes quantités de sédiments, mais la tête même reste vide par suite d'éboulements fréquents. La découverte de sédiments grossiers en divers points sur le fond du lit, et même au delà sur le fond de l'océan, suggère qu'un des résultats de ces éboulements de la tête du cañon est le transport vers la mer des sédiments, probablement par des courants de turbidité.

On ne peut dire que le problème de l'origine des cañons a été résolu. Les deux hypothèses, qui sont couramment admises sont :

— 1° les courants de turbidité ;
— 2° la submersion de cañons creusés par des rivières.

Les deux hypothèses, considérées isolément, ne semblent pas satisfaisantes.

A l'exception de leur partie la plus basse, peu creusée, les cañons semblent n'avoir aucune des caractéristiques que l'on attendrait s'ils avaient été effectivement creusés par des courants de turbidité. Il n'y a non plus aucune preuve que de tels courants puissent causer une érosion, et bien des observations montrent que ces courants transportent simplement les sédiments meubles produits par les glissements de terrains, sans même déranger le plancher de la gorge sur lequel ils se meuvent.

L'explication simple par une voussure vers le bas de la marge côtière n'est également pas en accord avec les caractéristiques des cañons. Une *explication possible* est qu'ils ont été creusés dans un passé assez éloigné et maintenus et un peu modifiés par les glissements de terrain et les courants de turbidité pendant une longue période de submersion.

## INTRODUCTION

If the various coastal ranges of the world were partially submerged beneath the oceans or seas which they face, the sea floor would descend directly from the shoreline without intervening shelf and the submarine slopes would be traversed by deep steep-walled canyons representing the submerged mountain slopes. Actually there are many canyons on the slopes of the sea floor and they have much in common with the canyons on mountain slopes, but the submarine canyons are found not only off coastal ranges but also off coastal plains and even broad deltas. Furthermore, continental shelves wide enough to indicate long periods of relative stability are located outside most coastal ranges and it is only in a few places that the canyons of the sea floor are directly connected with land canyons (1). Nor do the submarine canyons have the typical concave upward longitudinal profiles which would be expected from a hypothetical submergence of coastal ranges. Nor is there a clear erosion base on the submarine slopes to indicate the mouths of former land canyons. Finally the canyons are found off supposed coasts of emergence and submergence alike.

Difficulties with a simple submergence hypothesis have led to numerous attempts to explain submarine canyons as the product of erosion on the sea floor. In recent years this possibility of extensive submarine erosion has been given impetus by the discovery of a remarkable ability of supposed turbidity currents to carry coarse sediment down the slopes and out onto the floors of the ocean basins. On the other hand, there are many difficulties encountered by submarine erosion hypotheses and some new evidence has been discovered which favors a modified version of the submergence hypothesis. Accordingly, the purpose of this paper will be to bring readers up to date in the investigations and to point out the possible significance of the new data rather than to attempt any final explanation of a phenomenon that can scarcely be considered solved by any fair-minded investigator familiar with the facts.

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(1) Many of the largest canyons exist outside large rivers, but most of these rivers do not flow in land canyons near the sea coast.

## SUBMARINE CANYON CHARACTERISTICS

There has been some objection to the name *submarine canyon* and alternatives such as *seavalley, sea gully,* or *mock valley* have been suggested. However, the usual definition of a canyon is a *deep valley with high steep slopes.* Since this definition fits the characteristics of the submarine valleys which are under discussion it seems unwise to use any name other than canyon. For another type of elongate depression of shallow depth below the sea floor we can use the name *seavalley* as for example for the shallow valley which crosses the continental shelf off New-York Harbor.

Only a few submarine canyons have been sufficiently sounded so that we can obtain more than a generalized picture of their characteristics. Actually only the head of the canyon off La Jolla, California, has been sufficiently explored by a diver (see SHEPARD, 1949) and more recently by aqua-lung swimmers to obtain a clear picture of details. So far as other canyons are concerned, we must rely on a few samples and on such comparisons as can be made from their sounding lines with those of the well-known canyons. Some scientists feel that the California submarine canyons are unique (see for example DALY, 1942, p. 127) and differ to a marked degree from such canyons as the Hudson (1) off the east coast but there is actually no existing evidence to indicate that the east coast canyons, or any of the canyons off other coasts of the world, differ to a marked degree one from the other. In an earlier discussion (SHEPARD, 1948, pp. 209-228) a comparison was made of canyons from various parts of the world and their remarkable similarity was demonstrated. Subsequently some investigations have ben made of Mediterranean submarine canyons (BOURCART, 1950) and the same type of feature was revealed. Unless and until someone can produce evidence to the contrary, we seem to be faced with the conclusion that the only difference between California submarine canyons and those off other coasts is that the majority of California canyons extend in closer to the coast. Other apparent differences are probably the result of more investigation of California canyons. For example, more rock is known to exist and there is more evidence of narrow steep-walled rock ravines near the canyon heads than elsewhere. Actually the canyons off California do not extend out to greater depths than those of the other coasts nor do they penetrate farther inside the shelf edge. Along the parts of the California coast where the canyons extend to the shore the shelves are narrow. Canyons from many other areas head near the shore or even in estuaries.

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(1) A true canyon on the continental slope not to be confused with the Hudson Seavalley.

California happens to have been the only area where the data for these descriptions are available. Therefore the preceding discussion has been included as a justification for a semi-detailed description of some California canyons as type examples.

La Jolla and Scripps Canyons. — The location of Scripps Institution on the shore between the heads of La Jolla Canyon and its tributary Scripps Canyon (fig. 1) was purely coincidental, but so far as the canyon investigations are concerned it has proven to be a most happy coincidence. With the use of an amphibious vehicle we can actually leave our laboratories and 5 minutes later be at work over the submarine canyon heads. As a result we know in some detail

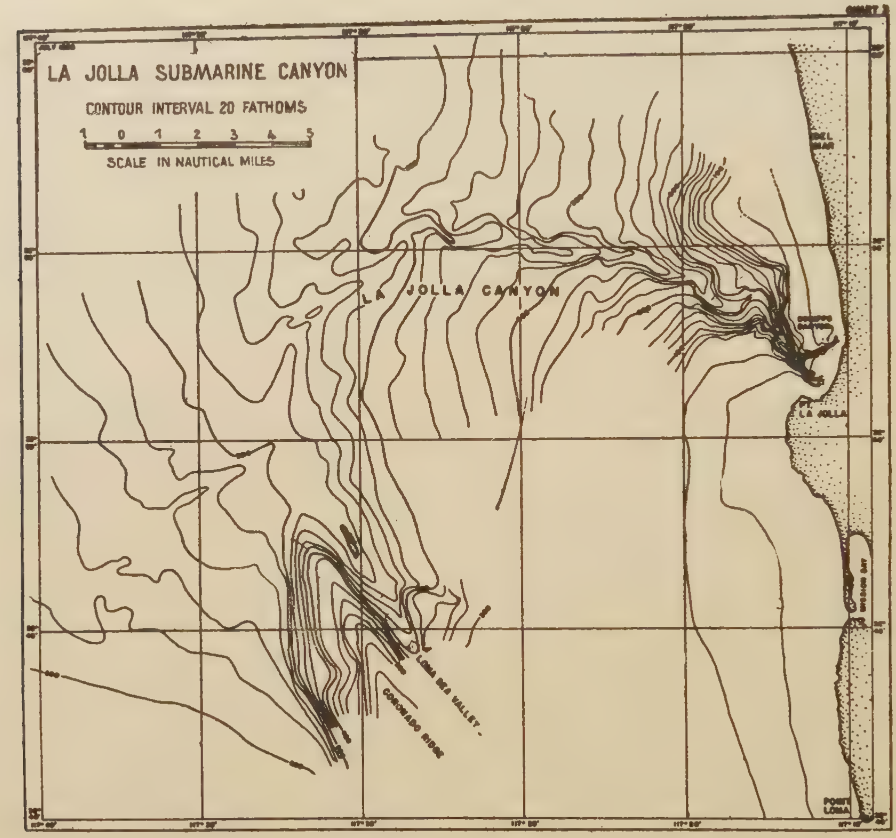
LA JOLLA SUBMARINE CANYON
CONTOUR INTERVAL 20 FATHOMS
1 0 1 2 3 4 5
SCALE IN NAUTICAL MILES
LA JOLLA CANYON
DEL MAR
SCRIPPS
PT. LA JOLLA
MISSION BAY
LOMA SEA VALLEY
CORONADO RIDGE
POINT LOMA

Figure 1.

what exists in that part of the sea bottom and are even aware of the depth changes which are taking place.

A general idea of the branching heads of Scripps Canyon can be obtained from figure 2. There are four shallow sandy valley heads near shore. Swimming down these depressions, as is possible with aqua-lungs, shows that they have rock outcrops beginning at about 50 foot (15 m.) depths. Beyond this point narrow ravines are encountered which deepen rapidly seaward and have precipitous and even overhanging rock walls. Fossils in these rocks have indicated an Eocene age. Along these walls there are entering tributaries, some of them coming in at grade but mostly as hanging valleys cut to small depths into the rock cliffs on the sides. In places the principal ravines plunge with essentially vertical steps into the deep abyss below. The floor of these canyon heads is ordinarily covered with sand but contains also a very large amount of kelp and eel grass which is undergoing decay and in places emitting clouds of methane bubbles resulting from this decomposition. The head of La Jolla Canyon has also a considerable number of narrow ravines with steep walls and steeply sloping floors. However, most of these ravines are cut into alluvium with cobble layers well represented. Other ravines

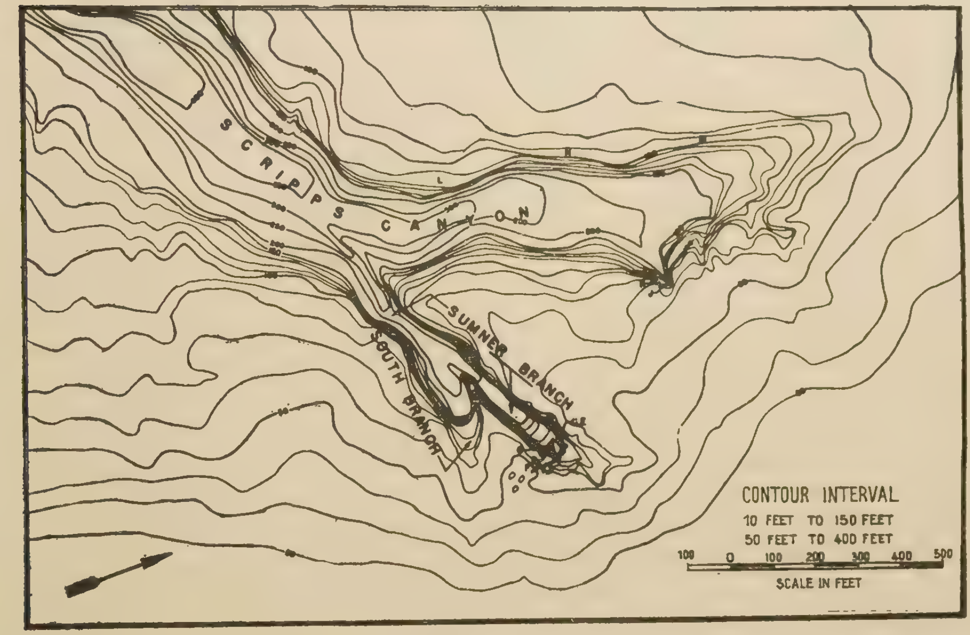

FIGURE 2.

have outcropping sandstone ledges. The floors of the gullies are more uniform in gradient than in Scripps Canyon but are not devoid of hanging valley relations. There are muddy sands on the floors of the ravines. Continuing down into greater depths the floor widens and is covered with sand, gravel, or mud, varying from place to place and probably from time to time.

Diving operations have extended to two hundred foot depths. Soundings, bottom sampling and submarine photography, however, seem to indicate that there is no appreciable change in the general character of Scripps Canyon out to the point where at a depth of about 1,000 feet it joins La Jolla Canyon. The outer Scripps Canyon apparently has continuous cliff walls, some of them essentially vertical, all precipitous. Going seaward the rock changes from sandstone and shale to conglomerate with a sandy matrix. The same rock types are found in the Eocene rocks of the cliffs north of Scripps Institution. Seaward of the gullied head La Jolla Canyon continues to slope seaward and is joined by various tributaries. The walls are less precipitous than Scripps Canyon and they have yielded large blocks of mudstone. Some fossils have been secured showing a Cretaceous fauna on one side and Eocene on the other.

Tracing the La Jolla Canyon seaward into San Diego Trough the walls attain a maximum height above the floor of 1,300 feet (430 m.) 4.5 miles beyond the confluence of the two canyons. Farther seaward there is a gradual change in character, which is observed first as a broadening of the floor although in places the floor is trenched by an inner gorge. Farther out the walls grow much lower and at depths of 2,500 feet (800 m.) the rim of the valley (no longer a canyon) rises as a low rounding ridge above the surroundings. Finally, as the slope merges into San Diego Trough the valley becomes insignificant and in places divides into distributaries. Thus with its surrounding ridges the outer valley calls to mind the lower course of a river on land with the ridges corresponding to natural levees. Sampling along the course of the outer valley has shown that the sands found shoreward in the true canyon bottom continue along the outer valley. These sands are interlayered with silt and clay sediments, the latter typical of the depth of water found at these places. The sand layers contain sparse Foraminifera but definite assemblages are characteristic of shallow water (PHLEGER, 1951) whereas the more abundant Foraminifera of the silts and clay are characteristic of the depths in which they are found.

The sand layers occur also on the floor of San Diego Trough beyond the end of the valley (LUDWICK, 1950 and SHEPARD, 1951 a).

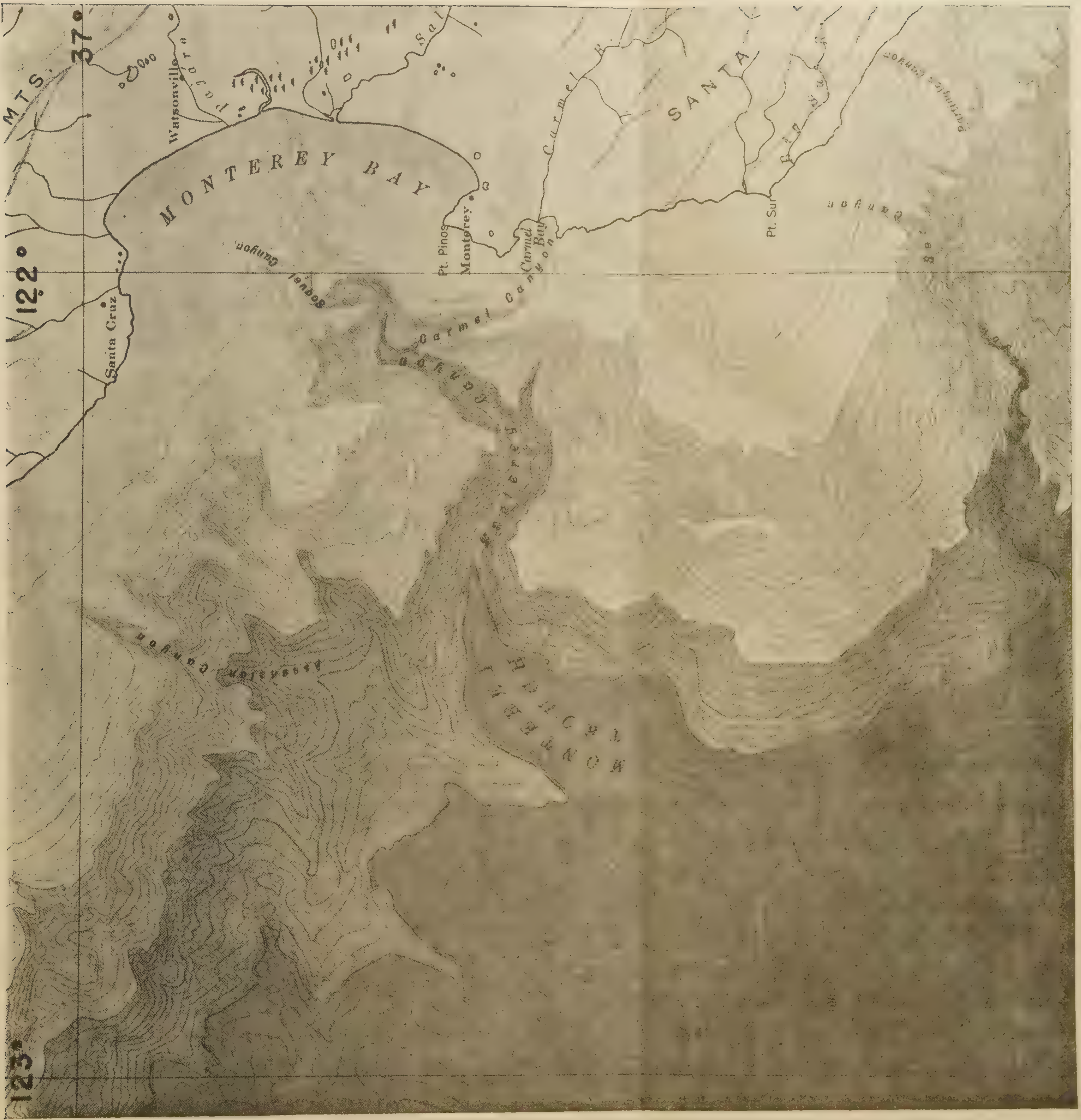
MTS.
37°
Watsonville
Pajaro
Sal
MONTEREY BAY
Soquel Canyon
Pt. Pinos
Monterey
Carmel Bay
Carmel Canyon
Carmel R.
SANTA
Big Sur
Pt. Sur
122°
Santa Cruz
Monterey Canyon
Ascension Canyon
MONTEREY
123°

Figure 3.

These erratic sands in San Diego Trough are more concentrated around canyon terminations. This was also reported for the sand distribution on the deep floor of the Atlantic outside the Hudson submarine canyon (HEEZEN *et al.*, 1951).

MONTEREY AND CARMEL CANYONS. — In many respects the canyon which winds out of Monterey Bay (Central California coast) is the most spectacular of any submarine canyon which is known (fig. 3). In one section it has dimensions which are remarkably similar to the Grand Canyon of the Colorado River. Unfortunately topographic details are lacking in the submerged canyon so that this comparison applies only to a single profile in which at least the average slopes and depths below surroundings are of the same order. The resemblance to the Grand Canyon extends also to the rock. At least one side of Monterey Canyon has yielded granite in the lower gorge and sedimentary rocks higher on the walls calling to mind the inner granite gorge of the Grand Canyon and the overlying Paleozoic series.

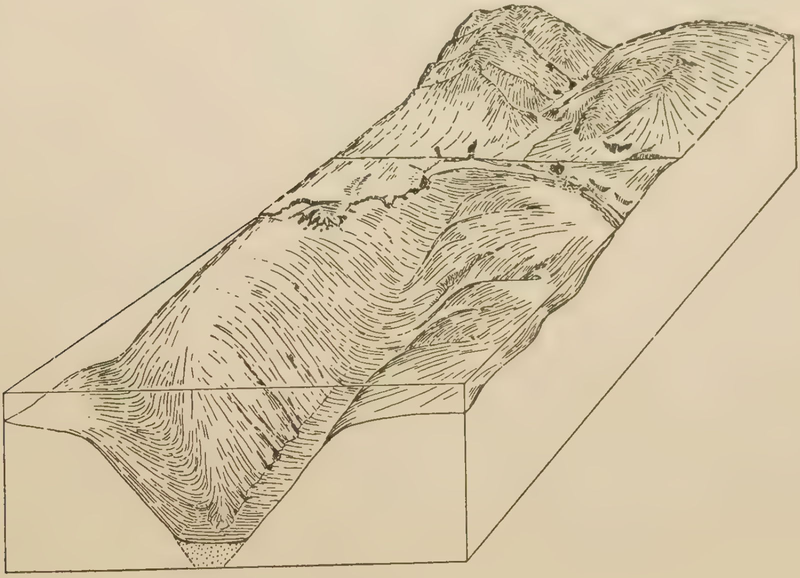

FIGURE 4.

Carmel Canyon, the principal tributary to Monterey Canyon, has been surveyed in detail in its inner portion (fig. 4). One branch extends within a stone's throw of the shore at the mouth of San Jose Creek. There can be little doubt but that the submarine canyon and the land canyon occupied by San Jose Creek are for all intents and purposes identical. Not only does the submarine canyon have the same shape, same slopes, and same tributary pattern but even the same type of granite is found on both walls.

In contrast to the rock gorge at the head of Carmel Canyon, the head of Monterey Canyon, which also extends within a stone's throw of the beach, has walls of unconsolidated sediment. As in the case of La Jolla Canyon there are a series of entering tributaries, all sloping outward at steep slopes toward the main canyon. Shoreward of Monterey Canyon lies the flat plain of the Salinas Valley so that there is a great contrast in gradient and in other characteristics betwen land and sea valleys at this point (WOODFORD, 1951). In dives made into the inner ravines of Monterey Canyon, Frank HAYMAKER obtained cores showing that the valley floors had deposits of alternating coarse clean sand and silty material with clean breaks at the contacts between the two types. These layers it should be noted were found near the canyon head where there is a high gradient.

Much of the outer part of Monterey Canyon has not been surveyed in enough detail to allow exact interpretation. It appears, however, that the deep gorge gradually changes into a trough along which the canyon has a wide floor but relatively steep walls. Recently a survey was made on the Navy Electronics Laboratory vessel E.P.C.E. (R) 857 using one of the new *Edo* Fathometers which provide fine detail at great depth. The results of this survey (DILL, DIETZ and STEWART, 1952) show that there is a delta-like feature at the outer extremity of Monterey Canyon which contains the distributary valleys and levee-type ridges found also at the outside of La Jolla Canyon. A core taken in one of these outer valleys contained alternating sand and mud layers.

LISTING OF CANYON CHARACTERISTICS. — Comparison of the above descriptions of a small California canyon with a huge canyon along another part of the California coast shows that there are very striking similarities despite the great contrast in scales, nature of canyon walls and character of the adjacent coasts. Furthermore, the characteristics described appear to be duplicated in almost all of the best surveyed submarine canyons along other coasts. It seems essential to have a listing of these characteristics as a basis for speculation concerning the canyon origins. The following list is provided for that purpose :

1. GENERAL NATURE OF CANYON HEADS. — The heads are most commonly made up of the juncture of a series of steep-graded steep-walled tributaries entering the main valley either with graded contacts or with hanging valley relations.

2. WALLS OF CANYON HEADS. — The walls consist either of solid rock, depending in character or nature on the country rock, or of unconsolidated sediment. Wall slopes may be vertical or overhanging in either type of wall.

3. RESEMBLANCE OF CANYON HEADS TO ADJACENT LAND VALLEYS. — Those canyons extending in close to shore have a shape closely comparable to the adjacent land valleys where the coast is mountainous but where the coast has low relief are very different from the land valleys.

4. DISTANCES BETWEEN COASTS AND CANYON HEADS. — About three-fourths of the known submarine canyons head within a mile of the coast, but better surveys may show this figure is too high because canyons heading far out from shore are known only off the United States, the only area where surveys have been sufficiently accurate and detailed to indicate the presence of canyons beyond the wide continental shelves.

5. RELATION OF CANYON HEADS TO ESTUARIES. — Most submarine canyons do not enter estuaries although there are some exceptions, notably the deep canyon in the entrance to the Congo Estuary and the deep canyon extending into Tokyo Bay.

6. CHARACTER OF MID-PORTIONS OF CANYONS. — Much less detail is available in the middle portions of canyons but these are the places where greatest depth below surroundings are found, commonly as much as 1,000 feet (300 m.) and rarely 5,000 feet (1.500 m.) or more. The courses of this portion of the canyons are usually winding and tributaries are probably less numerous than at the heads but exist in appreciable number wherever surveys are adequate to show them. The canyon floors are wider and have a surprising amount of sand and gravel deposit in them. The walls commonly consist of rock but the rock is coated with sediment in many places.

7. CHARACTER OF OUTER TERMINATIONS OF CANYONS. — We have little information from the outer extensions of the canyons, but valleys, commonly not more than one or three hundred feet (30 to 90 m.) deep, are found extending out to the flattened outer basins. Some of these valleys have levee-like ridges on the side and a few distributaries have been discovered.

DISTRIBUTION OF CANYONS. — The submarine canyons have been found along virtually all continental slopes where there are adequate soundings to make detection possible. Exceptions occur where slopes are unusually gentle, where slopes are bordered by island fringes, and along some slopes interpreted as recent fault scarps (SHEPARD, 1950). In some places canyons are closely spaced similar to land canyons on mountain slopes. Elsewhere the canyons are widely separated. Most of the large submarine canyons are located off large rivers and conversely most large rivers which enter the ocean have adjacent submarine canyons. On the other hand many of the canyons including some large ones have no apparent counterparts on land.

## SUBMARINE PROCESSES ASSOCIATED WITH SUBMARINE CANYONS

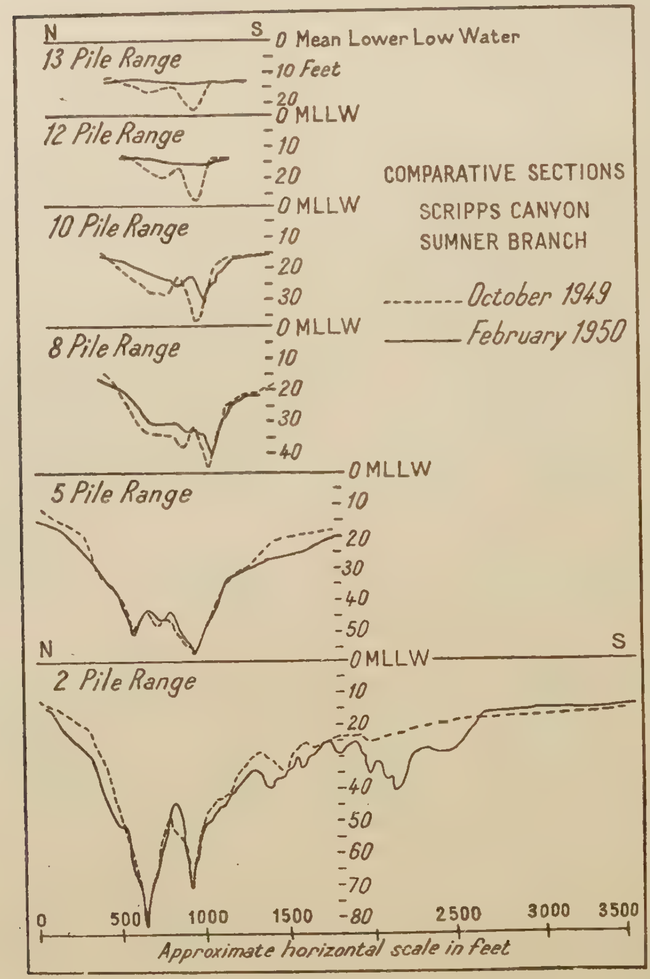

FIGURE 5.

BOTTOM CURRENTS. — The early suggestion that currents must operate along the canyons led to a considerable number of measurements (SHEPARD, 1948, pp. 61-66). *Ekman meters* were used in five California canyons and in two New England canyons at depths varying from 23 to 430 fathoms (42-800 m.). Some of the measurements were continued as long as 36 hours. Velocities up to about 0.5 miles per hour were observed about 3 feet above the bottom but much slower currents prevailed. The currents alternated between up canyon and down canyon directions with irregular periods, definitely non-tidal. Observations by a diver confirm the feeble nature of the currents as well as the reversal in direction. Furthermore, among the rather scarce canyon bottom photographs no ripple-marks have been found except in such shallow water that they are clearly the result of wave oscillation. Diving has shown a few ripples suggestive of down canyon movement in the shallow heads but no photographs of these are available as yet.

The absence of observed strong currents should not be construed as positive evidence that they do not exist. Such currents may occur at widely separated periods. Turbidity currents are implied to exist in the canyons because of the presence of coarse sediments at all depths along the canyon axes. It has been suggested that such currents might occur at the times when heavy rains are transporting a considerable amount of sediment into the ocean adjacent to the canyon heads. Several opportunities have been found to test this idea. Sediment traps have been in operation on the canyon floors during floods at La Jolla. The results to date have failed to indicate any strong down-canyon movement. In fact a trap placed in La Jolla Canyon before the great March flood of 1938 was recovered afterwards and only a moderate amount of sediment was obtained from it, the up canyon and down canyon compartments having approximately the same amount. On another occasion in the head of Scripps Canyon an unusually small amount of sediment was found in the trap suggesting that the flow of brackish muddy water over the surface may have stopped the normal effect of the waves in the canyon head. On still another occasion a small amount of silt was found in the up canyon bags suggesting a small down canyon flow. A dive made into the canyon head during a flood showed murky water but no appreciable current. Photographs in some shallow valleys off the City of San Clemente taken after a flood showed clear bottom water despite flows of muddy water observed moving out over the surface. However, this evidence does not exclude strong currents resulting from other causes.

Submarine landslides. — Another type of movement on the canyon floors in now well documented. Sliding of the unconsolidated sediments has been established in a number of the California canyon heads (Shepard, 1951 b). The existence of these slides was first suggested through the repetition of sounding lines. These lines are run by echo soundings along sufficiently sharp ranges so that repetition on the same day shows profiles which are almost identical. Many depth changes up to 20 feet between surveys at differents dates have been observed. In one canyon head at La Jolla deepening of 5 to 10 feet takes place at intervals of from about 6 months to a year (fig. 5). Between deepenings sediment brings depths back to approximately the old levels so that there is no clear evidence of net deepening. At Redondo Beach (near Los Angeles) a pier built into a canyon head was subject to one of these deepenings which caused the depth at the end of the pier to increase from 10 to 35 feet while puzzled fishermen on the pier continued to let out more line in order to get their sinkers to the bottom. Swirls of murky water boiled up from the sliding mass during this change. On December 25, 1951 there was a mild earthquake felt at La Jolla. Canyon head soundings on the next day showed a deepening of about 10 feet.

A collection of data on these submarine slides shows that some occur as a result of the trigger effect of earthquakes, others may be started by large waves working on the canyon heads, but still others take place without intervening earthquakes or large waves. Therefore, we must conclude that some slides are set off by the sediments exceeding the angle of repose. However, the complication of decaying marine plant material with the production of large quantities of gas is a factor which cannot be overlooked in producing instability in some canyons.

Additional evidence of canyon slides comes from aqua-lung observations. Landslide scars have been seen at various places where the sand on a slope has pulled away leaving a fresh escarpment. Also the swimmers on revisiting the same localities have noted great changes in the fill in the narrow ravines.

Unfortunately we do not know how far out these slides extend. The difficulty of establishing good ranges and of obtaining reliable echo sounding profiles in deep water has handicapped this phase of the investigation. With the expected improvement of sonic bottom scanning techniques, now good only to 100 feet, it may be possible to obtain profiles in relatively deep water which can be duplicated. The La Jolla and Carmel Canyons are so located that good clear-cut ranges on land objects can be established in positions where canyon floors have depths of at least 1,000 feet.

## SPECULATION CONCERNING SUBMARINE CANYON ORIGIN

TURBIDITY CURRENTS AND LANDSLIDES. — A very large number of origins other than subaerial erosion have been suggested for the submarine canyons, such as submarine faulting, upwelling, tidal currents, tsunamic currents, undertow, submarine artesian springs, and solution of the rocks under the ocean floor. Objections to these hypotheses have been presented in numerous publications (see for example JOHNSON, 1939 ; DALY, 1942, and SHEPARD and EMERY, 1941) and there appears to be little attempt in recent years to revive any of these inadequate hypotheses. On the other hand, the turbidity current hypothesis, has continued since it was first suggested by DALY (1936) to attract wide attention and recently has been given new impetus.

The turbidity currents are known to exist from experiments and from observations in reservoirs. They obtain their motive power through higher density largely the result of suspended sediment in the water. It happens that turbid water masses have only a very slow mixing with clear adjacent water masses and as a result a turbid current can flow for great distances along the bottom before losing its identity. At first it was supposed that these currents consisted only of mud suspensions, but experiments by KUENEN (1948) established that sands and even gravels will flow down slopes maintaining their identity.

Since our observations at La Jolla appear to eliminate land floods as a cause of turbidity flows on the sea floor, another cause must be sought. The most likely alternative appears to be landsliding which may be capable of throwing sediments into suspension sufficiently to establish turbidity flows. Our experiments in 1950 with explosives set off on the floor of Scripps Canyon failed to produce any appreciable flows although clouds of sediment boiled up to the surface over the explosion center and small amounts of sediment could be traced with turbidity meters down canyon a maximum distance of 700 feet (SHEPARD, 1951 a, p. 60).

The discovery of numerous sand layers both along submarine canyons and out in the basins and troughs beyond the canyons (ARRHENIUS, 1950, ERICSON et al., 1951, and SHEPARD, 1951) has suggested that turbidity currents are responsible and therefore that they have an extraordinary carrying power, far greater than would have been supposed possible. Actually there is little evidence to show that these coarse layers are the result of turbidity currents, but we do know that many are related in location to submarine canyons and some contain some shallow water benthonic organisms (PHLEGER, 1951). Beyond that we must simply interpolate results of experiments which were made under rather unnatural conditions. On the other hand, no adequate alternative explanation for the deep water sands has been offered.

If we assume that turbidity currents are the cause of the deep water sands and gravels, we can then speculate further regarding the capability of these currents to produce erosion. Recently HEEZEN and EWING (1952), have called attention to the 1929 Grand Banks earthquake and the cable breaks which occurred at progressively later periods down the slope from the epicentral area. These breaks they believe were the result of a turbidity current set up by the earthquake. Judging from the time of the breaks, such a current is inferred to have had an early velocity of about 60 miles an hour down a 0.5 % slope near the epicenter and a velocity of 14 miles per hour across the outer 0.05 % slope (see also KUENEN, 1952). The current may even have moved up over a ridge along a portion of its outer course. The cables were broken by some type of movement which caused a great twisting effect. The breaks took place over a width of 160 miles indicating great dispersal. This is indeed an interesting piece of evidence, but here again we are proceeding on an insecure foundation. How do we know that were not a series of landslides all started by the earthquake which broke the cables at varying times, the first breaks occurring where the landslides were most violent, that is, near the epicenters ? The present surveys are quite inadequate so there is no reason to doubt that many slopes exist over the area steep enough for slides. Alternatively there may have been progressive faulting movements along the sea floor of a nature which were too slow to produce clear cut records on the seismographs. There is no proof that the burying of large portions of one of the outer cables was produced at the time when the cable parted. The velocity of 60 miles an hour for a suspension current raises some interesting hydraulic considerations. Surely the presence of the overlying water would cause some friction which would interfere with the progress of the turbidity current. Even without this friction it seems most unlikely that a mass of turbid water could move down a slope of 0.5 % at such an enormous rate. At least this portion of the evidence should be classified as highly conjectural.

The other evidence of the erosive power of turbidity currents has been found. The finding of delicate fossil impressions on mudstone surfaces under the sands of turbidity current transport (KUENEN and

Migliorini, 1950, pl. 5 A) shows that the mere transport of coarse sediment does not of itself indicate erosion. It has been suggested that the turbidity currents are erosive at the canyon heads and mere transporters of sediments along their lower courses (recent paper read by Ph. H. Kuenen). However, the discovery of alternating mud and sand layers in the steep head of Monterey Canyon (referred to previously) seems to imply that even here the agency which transports the coarse sediment lacks the ability to remove the mud layers deposited in the interim between flows.

Another approach to the problem of erosion by turbidity currents comes from observations on the fronts of deltas. Valleys of small dimensions are known to exist on these delta slopes. These valleys have been referred to as indications of erosion. However, the study of Lake Meade (Gould, 1951) leaves little doubt but what these valleys are simply depressions in the advancing fronts of deltas, the crease being maintained by more rapid deposition on either side. No one has shown that any of these valleys are actually cutting back into the delta and yet the delta fronts are steep, slides are common, the sediment is easily eroded, and relatively heavy water is introduced continuously by the rivers and intermittantly there are slides down the delta fronts. What better place could there be for erosion on a submerged slope ? To my way of thinking there is no greater stumbling block to the acceptance of the turbidity current hypothesis than these delta front observations.

## SUBMERGED RIVER-CUT CANYONS

Many authors have explained the canyon by river erosion, but there has been little agreement on the mechanism of exposing the slopes to subaerial action. Among recent suggestions are : (1) temporary upbulging of the continents along shear planes (Emery, 1950), (2) alternate sinking and rising of the ocean basins due to changing density in the sima (Von Engeln, 1950), and (3) earth shrinkage accompanied by downward movement of crustal segments under the ocean basins followed after an interval by subsidence of the continental platforms (Landes, 1952). The last two consider the emergence was during the Pleistocene and hence run counter to the new evidence that submergences are much more remote.

In favor of the submergence hypothesis. — The aqua-lung divers from Scripps Institution who have swum around the shallow head of Scripps Canyon have all been impressed with the resemblance of the cliffs and their projecting ledges, narrow ravines, and hanging valleys to subaerially eroded features such as appear above water on the adjacent land. Even if landslides and resulting turbidity currents could account for the main valleys, it would seem surprising if in the absence of rainwash and other subaerial weathering effects the walls could develop such a subaerial appearance.

This highly suggestive evidence favoring stream excavation does not necessarily apply to the deep canyons. It is generally believed that sea level lowerings of the order of 300 feet have accompanied the maximum ice advances of the Pleistocene. As a result of this lowering the canyon heads would have been exposed to subaerial action at a time estimated as approximately 10,000 years ago. However, given a shelf of ordinary depth, that is, 300 to 500 feet below present sea level (1), a lowering of 300 feet would not produce canyon cutting outside a steep coast, such as is found at the head of Scripps Canyon, because the runoff would be slowed where it hit the low shelf gradients and there would be fan-building rather than cutting. However, if a pre-existent valley with a high gradient were exposed by the lowering, erosion could occur.

If, in turn, only the inner canyon at depths of less than 300 feet were subaerially eroded, one would expect a marked change in canyon characteristics at greater depths. So far as soundings and photographs are available, this change cannot be demonstrated. Further examination of figures 2 and 4 shows that at least Scripps and Carmel canyons continue seaward without a break in their continuity. A careful examination of soundings in other canyons has failed to show appreciable nick points at or near 300 feet.

The subaerial erosion hypothesis has several theoretical advantages over any submarine erosion hypothesis. Rain falling on an uneroded slope soon develops a concentration of runoff along some initial irregularities. As a result when erosion has proceeded through the soft sediment mantle and encountered relatively resistant rock, the increasingly concentrated flow causes erosion to continue at the same place. On the other hand if landslides and resulting turbidity currents could produce erosion on a submerged slope, this erosion would proceed principally at those places where there were slides in the overlying unconsolidated sediments. In localities where slides had removed the cover, exposing the resistant rock beneath, erosion would come to a virtual standstill, but the slides would continue on either side bringing the surface down to the rock level (fig. 6). As a result, no major canyons would develop, but a series of small valleys would form and these would tend to lose their valley characteristics after reaching rock base. Actually no submarine slope has been found where the slides have removed even a large part of the sediment from the slope. Accordingly the submarine erosion hypothesis fails to account for the numerous large submarine canyons cut into firm rock formations.

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(1) These are certainly not a product of post-glacial erosion. See for example Dietz and Menard (1951).

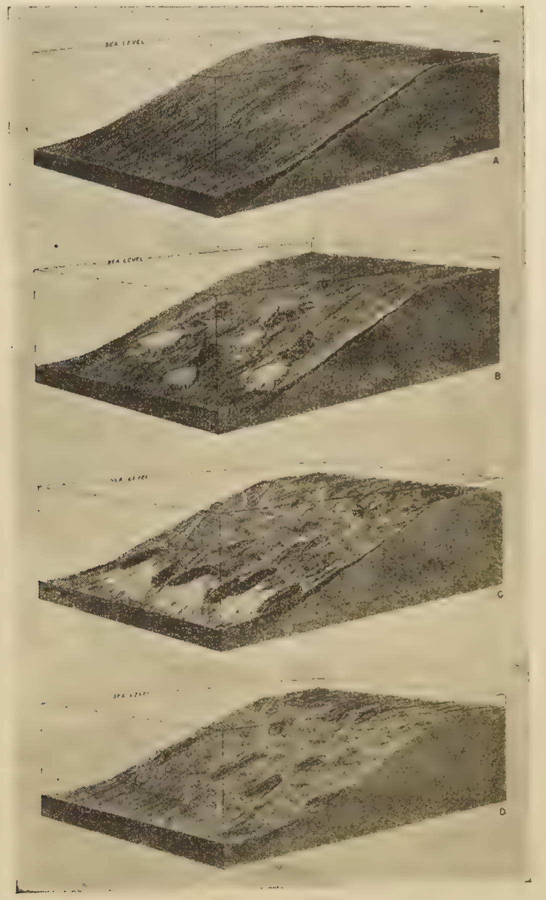

Figure 6.

The finding of submarine canyons extending into estuaries has proven to be a considerable embarrassment to the advocates of submarine erosion. The well known canyon of the Congo (see Veatch and Smith, 1939, pl. 2, and for another interpretation Shepard, 1948, fig. 78) is particularly troublesome since it heads at the mouth of one of the largest rivers in Africa. If one assumes that such estuary-penetrating canyons as Congo Canyon, Tokyo Canyon (Shepard, 1948, fig. 74) and Carmel Canyon are actually submerged river canyons, one is led to wonder what differentiates any of these canyons from other typical submarine canyons. Granting a subaerial origin for example for Carmel Canyon, what was happening in Monterey Bay when the adjacent land was sufficiently emerged to allow the cutting of the Carmel tributary ? If Monterey Bay was also greatly elevated why did not the rim in the Salinas valley cut a canyon into Monterey Bay ? The obvious answer is that it did. However, Monterey Canyon has been used as an example of a feature which discredits the subaerial erosion hypothesis (Woodford, 1951).

Difficulties encountered with subaerial erosion. — The preceding discussion may appear to throw all of the weight in favor of subaerial erosion, but there are plenty of objections, particularly to any simplified explanation. Possibly the most formidable obstacle has come from the tracing of various canyons out to the floor of the deep basin at the foot of the slope. One might expect to find a base at which subaerial erosion ceased, but canyons in general do not appear to stop midway down the slope. On the other hand, there should be no reason for a canyon cut by submarine erosion to terminate until it reached the bottom of the slope.

Many geologists have found the almost universal distribution of canyons a serious obstacle to the acceptance of the subaerial hypothesis. Geological studies on land apparently indicate that some coastal areas have been subsiding over a long period, whereas others have been rising over equally long periods, but the canyons, if subaerial in origin, imply almost universal subsiding of the continental margins. Furthermore, the rough accordance of the outer edge of the continental shelves which for the most part lie at depths of 300 to 500 feet, suggests a long period of still stand. As one means of explaining this enigma, I suggested (Shepard, 1936) that the glaciers might have been much larger than generally assumed so that sea levels were lowered thousands instead of hundreds of feet. This idea, however, must be abandoned because the recent borings into coral reefs and the dredgings of seamounts (guyots) show that the submergences extend back to early Tertiary or into the Cretaceous periods. Furthermore canyons have recently been discovered in the Arctic (A. Carsola, 1952) where ice must have existed during glacial stages.

Reference also has been made to the gradients of submarine canyons which are for the most part adjusted with gradients of valleys on the adjacent lands (Woodford, 1951). Furthermore, attention has been called to the absence of canyons along many slopes and to the scarcity of tributaries (¹). These objections are serious, if applied to an hypothesis of relatively recent submergence, and at least indicate that subaerial erosion is not the only factor producing the present topography.

The finding of Pleistocene and even possible Recent formations on the walls of the canyons (see Woodford, 1951 ; Crowell, 1952, and Shepard, 1949) has indicated that erosion of relatively recent age has taken place and thus would imply either that submergence has been very recent or that submarine erosion is still occurring. Since straight coasts lacking estuaries are so common inside canyon heads and since the depths of the continental shelf margins in the same areas are so close to world averages, recent submergence, other than post glacial sea level rise, appears to be eliminated.

Composite origin. — The preceding discussion suggests that neither the submarine erosion hypothesis nor the subaerial erosion hypothesis are capable of explaining the submarine canyons. This has led me to offer a composite hypothesis which combines subaerial erosion with landslides and turbidity currents (Shepard, 1951 c, 1952). A possible sequence of events which might explain the facts now available is as follows :

1. General subaerial erosion of canyons resulting from emergence of a considerable portion of what are now submarine slopes. This erosion is thought to have occurred during one or more periods possibly extending as far back as the Cretaceous.

2. Delta formation on the sea floor outside the exposed slopes accompanying the erosion of the canyons.

3. Gradual submergence of the canyons over many millions of years.

4. Deposition of sediment in the heads of the canyons alternating with landslides which in turn produce turbidity currents.

5. Transportation of the sediment basinward by the turbidity currents with the production of channels across the fronts of the submerged deltas partly as a result of the building of natural levees on the sides of the active flows.

6. Further modification of the delta fronts by independent slumping which increased valley dimensions.

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(1) Recent detailed surveys have shown that there are more tributaries and fewer canyon-free slopes than indicated in earlier surveys.

7. Deposition of sediment on subsiding continental margins, building such shelves as those on the east coast of the United States.

8. Maintenance of the canyons by sliding and turbidity currents during the building of shelves on either side.

9. Pleistocene lowering of sea level by a few hundred feet exposing the canyon heads to renewed subaerial erosion and thus developing the ravines and rock gorges into which the divers and swimmers have penetrated at La Jolla.

10. Contemporaneous cutting of terraces on shelves by wave action at the lowered levels.

11. Post-glacial rise of sea level with continued slides in the canyons and continued deposition locally on the shelves on either side. These post-glacial slides could account for the exposure of Recent sediment on canyon walls.

This sequence of events may seem highly speculative, but there is a growing mass of information which appears to support the idea. For example, there are numerous wells along coastal areas which have yielded thousands of feet of shallow water deposits. Thus the wells on the east coastal plain of the United States, particularly at Cape Hatteras, show thousands of feet of alternating shallow water marine and continental sediments. The same is true all along the Gulf Coast. Even in California, where it is often assumed that there has been general elevation, there are well logs indicating thousands of feet of marine and continental sediments inside many of the coasts where the canyons are located (1). Outside the California coast, flat-topped banks and seamounts have yielded rounded cobbles down to depths of about 3,000 feet (SHEPARD and EMERY, 1941). Furthermore along the rim of southeast Asia the atolls are proving to be subsiding masses (see for example LADD et al., 1948). Subsidence has even extended out into the deep oceans where it is shown by the dredgings on the flat-topped seamounts (HAMILTON, 1951). Whatever force caused this subsidence may have alternated with forces producing temporary emergence exposing the marginal slopes to subaerial erosion. Such movements would be akin to those shown by the record of subsiding geosynclines, where unconformities show a reversal of the general trend.

The maintenance of canyons by sliding and turbidity currents over long periods of time may seem unlikely, but at least we have the evidence that the canyon heads at La Jolla are being maintained now despite active sedimentation. Still more significant is the existence of submarine canyons at the very mouths of rivers, like the Congo, which shows that submarine processes are actively in operation. Is it not illogical to think, on the one hand, that submarine processes could not flush recent sediments from already excavated canyons, but on the other hand, that these same processes could cut the canyons through thousands of feet of rock ?

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(1) In the Ventura basin some of the sediments may have been deposited in water 5,000 feet deep, but the sediment column includes nearly 20,000 feet (Natland and Kuenen, 1951).

Many of the difficulties with the earlier hypotheses appear to be eliminated by this joint process. Thus the difficulty in explaining the deep rock gorges by turbidity currents is avoided. The failure of canyon gradients to coordinate with adjacent land valleys is explained if the canyons are very old and have been long subject to marine modification while land valleys have also undergone extensive changes. The continuation of the sea valleys out to the base of the slopes should no longer constitute a difficulty if these outer valleys are of submarine origin. Finally, the absence of deep canyons in the steep fronts of present day deltas is consistent with an hypothesis which does not call for active marine erosion.

No doubt there are many weaknesses in this composite hypothesis. Much more exploration of the canyons is needed before any thoroughly satisfying explanation can be given.

## BIBLIOGRAPHY

Arrhenius G. (1950). — The Swedish Deep Sea Expedition. The geological material and its treatment with special regard to the eastern Pacific. *Geol. Fören. Förhandl.*, Bd. 72, H. 2, pp. 185-191.

Bourcart J. (1950). — Le socle continental de Toulon à la frontière espagnole. *Centre de Recherches et d'Etudes Océanogr.*, Conf. N° 3, 10 pp.

Carsola A. (1952). — Marine Geology of the Arctic Ocean and Adjacent Seas. (Doctoral Thesis, Scripps Inst.).

Crowell J. C. (1952). — Submarine canyons bordering central and southern California. *Jour. of Geol.*, Vol. 60, N° 1, pp. 58-83.

Daly R. A. (1936). — Origin of submarine canyons. *Am. Jour. Sci.*, 5 th series, Vol. 31, pp. 401-420.

— (1942). — The Floor of the Ocean. Chapel Hill, Univ. of North Carolina Press, 177 pp.

Dietz R. S. and Menar H. W. (1951). — Origin of abrupt change in slope at continental shelf margin. *Bull. A. A. P. G.*, Vol. 35, N° 9, pp. 1994-2016.

Dill R. F., Dietz R. S. and Stewart H. B. (1952). — Deep-sea channel of the Monterey Canyon. Abstract, Cordilleran Section, *Geol. Soc. of Am.*

EMERY K. O. (1950). — A suggested origin of continental slopes and of submarine canyons. *Geological Mag.*, Vol. LXXXVII, N° 2, pp. 102-104.

ERICSON D. B., EWING Maurice and HEEZEN B. C. (1948). — Deep-sea sands and submarine canyons. *Bull. Geol. Soc. of Am.*, Vol. 62, pp. 961-965.

HAMILTON E. L. (1951). — Sunken islands of the mid-Pacific mountains. Abstract, *Bull. Geol. Soc. of Am.*, Vol. 62, N° 12, Part 2, p. 1502.

HEEZEN B. C. and EWING Maurice (1952). — Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. *Amer. Journ. Sci.*, vol. 250.

JOHNSON D. W. (1939). — The origin of submarine canyons. Columbia University Press.

KUENEN Ph. H. (1948). — Turbidity currents of high density. *International Geol. Congr.*, Part VIII, pp. 44-52.

KUENEN Ph. H., and MIGLIORINI C. I. (1950). — Turbidity currents as a cause of graded bedding. *Jour. of Geol.*, Vol. 58, N° 2, pp. 91-127.

KUENEN Ph. H. (1952). — Estimated Size of the Grand Banks Turbidity current. *Amer. Jour. Sc.*, vol. 250, pp. 874-884.

LADD H. S., TRACEY J. I. and LILL G. G. — Drilling on Bikini Atoll, Marshall Islands. *Science*, Jan., pp. 51-54.

LANDES K. K. (1952). — Our shrinking globe. *Bull. Geol. Soc. of Am.*, Vol. 63, N° 3, pp. 225-239.

LUDWICK J. C. (1950). — Deep water sand layers off San Diego, California. *Doctoral Thesis*, Scripps Inst. of Oceanogr..

NATLAND M. L., and KUENEN Ph. H. (1951). — Sedimentary history of the Ventura Basin, California, and the action of turbidity currents. *Soc. of Econ. Paleontologists and Mineralogists*, Spec. Pub. N° 2, pp. 76-107.

PHLEGER F. B. (1951). — Displaced Foraminifera faunas. *Soc. of Econ. Paleontologists and Mineralogists*, Spec. Pub. N° 2, pp. 66-75.

SHEPARD F. P. (1936). — The underlying causes of submarine canyons. *Nat. Acad. of Sci.*, Vol. 22, N° 8, pp. 496-502.

— (1948). — Submarine Geology. Harper & Bros. 338 pp.

— (1949). — Terrestrial topography of submarine canyons revealed by diving. *Bull. Geol. Soc. Am.*, Vol. 60, pp. 1597-1612.

— (1950). — Part III of : 1940 E. W. SCRIPPS cruise to Gulf of California. *Geol. Soc. of Am.*, Memoir N° 43, 32 pp.

— (1951 a). — Transportation of sand into deep water. *Soc. of Econ. Paleontologists and Mineralogists*, Spec. Pub. N° 2, pp. 53-65.

— (1951 b). — Mass movements in submarine canyon heads. *Trans. Am. Geoph. Union*, Vol. 32, N° 3, pp. 405-418.

— (1951 c). — Submarine erosion, a discussion of recent papers. *Bull. Geol. Soc. Am.*, Vol. 62, N° 12, pp. 1413-1418.

— (1952). — Composite origin of submarine canyons. *Jour. of Geol.*, Vol. 60, N° 1, pp. 84-96.

SHEPARD F. P., and EMERY K. O. (1941). — Submarine topography off the California Coast. *Geol. Soc. Am.*, Special Paper N° 31.

VON ENGELN O. D. (1950). — Submarine canyons and the ice age : a discussion. *Jour. of Geol.*, Vol. 58, N° 2, pp. 161-163.

VEATCH A. C., and SMITH P. A. (1939). — Atlantic submarine valleys of the United States and Congo submarine valley. *Geol. Soc. Am.*, Special Paper N° 7.

WOODFORD A. O. (1951). — Stream gradients and Monterey Sea Valley. *Bull. Geol. Soc. Am.*, Vol. 62, pp. 799-852.

ACHEVÉ D'IMPRIMER A ALGER LE 20 NOVEMBRE 1953
SUR LES PRESSES
DES IMPRIMERIES LA TYPO-LITHO ET J. CARBONEL RÉUNIES
FONDÉES A ALGER EN 1833

PAPIER LISSÉ PUR ALFA D'ALGÉRIE 90 GRAMMES
FABRIQUÉ A BABA-ALI (ALGER)
DANS LES USINES DE LA CELLUNAF
(COMPAGNIE NORD-AFRICAINE DE CELLULOSE)